



Risø energy report 2. New and emerging bioenergy technologies

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Risø Energy Report 2

New and emerging bioenergy technologies

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Preface

Three growing concerns – sustainability (particularly in the transport sector), security of energy supply and climate change – have combined to increase interest in bioenergy. The trend towards bioenergy has been further encouraged by technological advances in biomass conversion and significant changes in energy markets.

We even have a new term, “modern bioenergy”, to cover those areas of bioenergy technology – traditional as well as emerging – which could expand the role of bioenergy. Besides its potential to be carbon-neutral if produced sustainably, modern bioenergy shows the promise of covering a considerable part of the world’s energy needs, increasing the security of energy supply through the use of indigenous resources, and improving local employment and land use. To make these promises a reality, however, requires further R&D.

This report provides a critical examination of modern bioenergy, and describes current trends in both established and emerging bioenergy technologies. As well as examining the implications for the global energy scene, the report draws national conclusions for European and Danish energy supply, industry and energy research.

The report presents the status of current R&D in biomass resources, supply systems, end products and conversion methods. A number of traditional and modern bioenergy technologies are assessed to show their current status,

future trends and international R&D plans. Recent studies of emerging bioenergy technologies from international organisations and leading research organisations are reviewed.

The report is based on internationally-recognised scientific material, and is fully referenced. The presentation of current global developments in bioenergy is based on the latest information from authoritative sources including the IEA, the World Energy Council (WEC) and World Energy Assessment.

This is the second in the series of Risø Energy Reports, which are published to provide global, regional and national perspectives on current and future energy issues. Individual chapters have been written by Risø staff members and leading Danish and international bioenergy experts, and the whole report has been refereed by an independent panel of international experts. Our target group is colleagues, collaborating partners, customers, funding organisations, the Danish ministries and agencies as well as international organisations such as the EU, the IEA and the UN.

Hans Larsen
Jens Kossmann and
Leif Sønderberg Petersen

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Summary and main conclusions

HANS LARSEN, JENS KOSSMANN AND LEIF SØNDERBERG PETERSEN, RISØ NATIONAL LABORATORY

Bioenergy is energy of biological and renewable origin, normally derived from purpose-grown energy crops or by-products of agriculture, forestry or fisheries. Examples of bioenergy resources are fuel wood, bagasse, organic waste, biogas and bioethanol. Bioenergy is the only renewable energy source that is available in gaseous, liquid and solid forms.

Growing concern about the sustainability of energy supplies (especially in the transport sector), supply security and the need to take action on climate change have all served to increase interest in bioenergy. Technological advances in biomass conversion, combined with significant changes in energy markets, have stimulated this trend and led to the invention of a new term, “modern bioenergy”, covering a number of traditional and emerging areas of technology. The world’s government-funded energy-related R&D is decreasing, but bioenergy R&D has increased in both relative and absolute terms during the last decade or so.

Today bioenergy provides 11–14% of the world’s energy supply, but there are significant differences between industrialised and developing countries. In many developing countries bioenergy is the most important energy source. The use of bioenergy in the industrialised countries, on the other hand, varies from 4% in the USA to 20% in Finland. Danish energy production from biomass in 2001 was approximately 42 PJ, or 5% of the country’s total energy consumption of 829 PJ.

In principle, modern bioenergy could cover all the world’s energy requirements, but its real technical and economic potential is much lower. The annual theoretical potential of bioenergy has recently been estimated at 2900 EJ, but the present practical technical and economic potential is estimated to be 270 EJ. Current use of bioenergy is estimated to be only around 55 EJ.

Supply systems – harvesting, collection, handling and storage – are a great technical challenge for modern bioenergy. Biomass is a local and bulky resource, so transport costs can be a barrier. This obstacle can be overcome by developing locally-applicable technologies to convert bulky raw materials into energy-dense solid, liquid or gaseous fuels.

Land for the production of bioenergy resources is another key issue, since competition for land could lead to reduced levels of food security. In many developing countries, however, food and fuel production can be integrated in complementary land-use systems. In industrialised countries, much of the land being removed from agricultural production, such as EU “set-aside”, could be used to produce bioenergy.

The end products of bioenergy systems can be used for:

- transport;
- electricity supply; and
- heating.

In the transport sector, biodiesel produced from vegetable oils could play an important role. Further technical advances could also create “biolubricants” from vegetable oils. Another promising transport fuel is ethanol produced from plant materials by biological processes.

For electricity production, the use of bioenergy crops is an effective way to mitigate the greenhouse effect by reducing the use of fossil fuels. Using biomass for heat and power production increases the security of energy supply by lowering the demand for non-renewable fossil fuels. In the near future, solid oxide fuel cells (SOFCs) offer a promising route to efficient electricity production. For sustainable power, we should continue to develop gasification and fuel cell conversion systems based on biomass.

Conversion technologies need to be chosen to suit the energy service in question: heat, electricity or transport fuel. Thermochemical processes convert biomass into liquid or gaseous energy carriers that have higher energy densities and more predictable and convenient combustion characteristics than the raw materials from which they are made. Catalytic liquefaction can produce fuels of even higher quality and energy density.

Another conversion technology, the use of micro-organisms to produce ethanol, is an ancient art. These micro-organisms are now regarded as biochemical “factories” for converting organic waste into gaseous or liquid fuels. Modern biotechnology could contribute to the development of CO₂-neutral power generation systems in two distinct ways. The first of these is traditional or “white” biotechnology, which in this context deals with the use of fermentation processes and enzymes in the downstream processes of biomass conversion. This area of technology is firmly established and forms an integral part of the fermentation processes described in this report.

The other area is “green” biotechnology, which uses genetic engineering to tailor the characteristics of biomass to optimise its performance as an energy resource. Such technology is still at the emerging stage and has so far been only superficially explored.

To date, almost the only biomass types to have been investigated as energy sources using green biotechnology have been those that are already available from traditional cropping or foresting systems. The challenge is

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now to establish small-scale prediction systems that will allow the establishment of structure-function relationships between the composition of biomass and its convertibility in energy conversion systems. This will allow us to explore and create biodiversity in energy crops, as well as improving the performance of bioenergy systems. Many “top ten” lists of emerging generic technologies include modern biomass-based energy systems. However, many bioenergy technologies are still wide open for development. The future of bioenergy depends strongly on the interactions between specific emerging energy technologies and more generic developments in biotechnology and information technology.

Key messages

The most important driving forces for modern bioenergy are:

- security of supply, based on to the use of domestic resources;
- local employment and local competitiveness;
- local, regional and global environmental concerns; and
- land use aspects in both developing and industrialised countries.

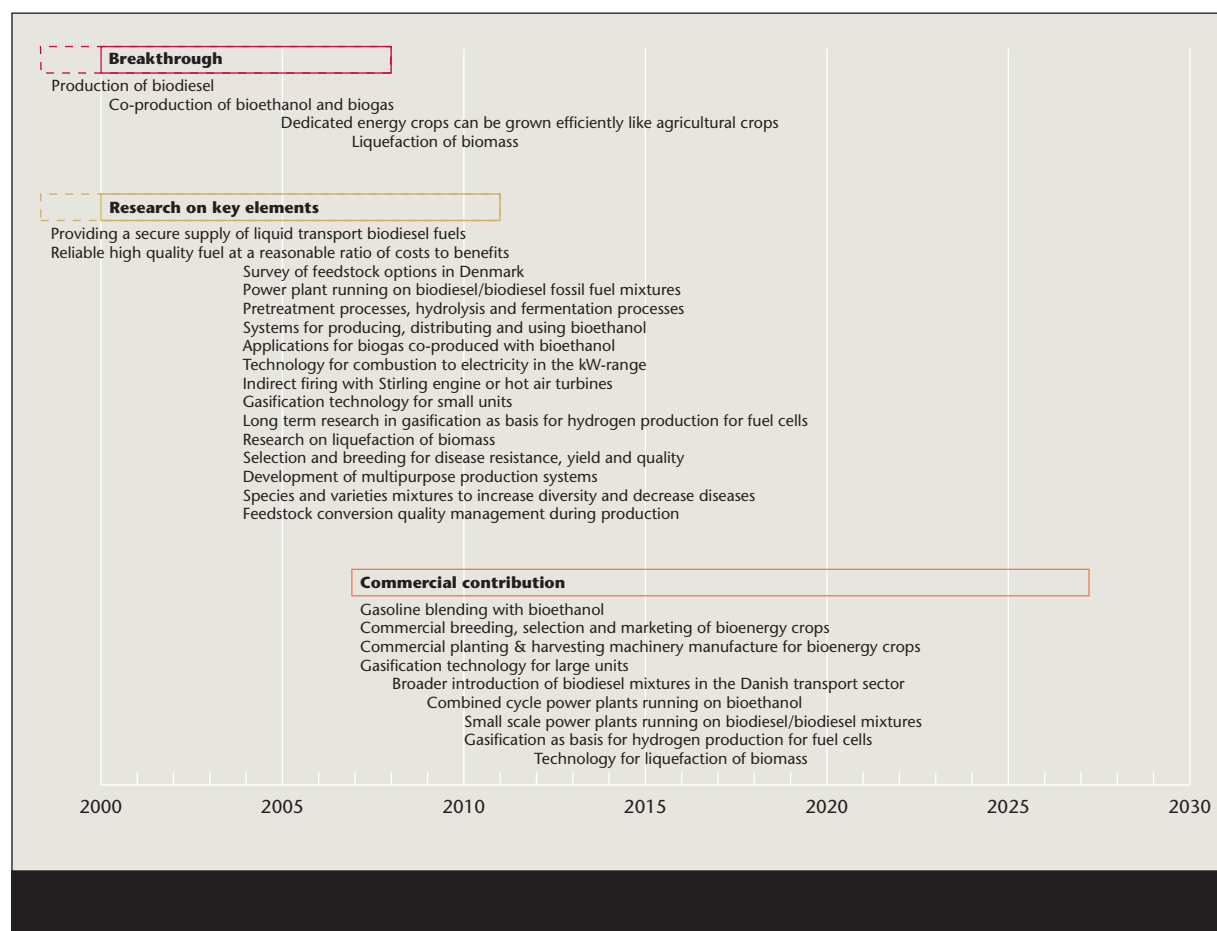
Barriers are:

- the competitiveness of the various bioenergy technologies varies from close to competitive to far from;
- the competitiveness is strongly depending on e.g. the amount of externalities included in the cost calculations;
- in general bioenergy technologies need to be moved down the learning curve;
- resource potentials and distributions;
- costs of bioenergy technologies and resources;
- lack of social and organisational structures for the supply of biofuels;
- local land-use and environmental aspects in the developing countries; and
- administrative and legislative bottlenecks.

These barriers can be lowered through dedicated interventions by both public and private sector entities, focusing on:

- development and deployment of more cost-effective conversion technologies, especially those that yield end-products – solid or liquid – with high energy densities;

Figure 1. Time scale from break through to commercial contribution



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- development and implementation of improved, dedicated, bioenergy crop production systems;
- establishment of bioenergy markets and organisational structures for transporting and delivering bioenergy resources and products; and
- valuation of the environmental benefits for society e.g. on carbon balance.

Our conclusions are:

- simply burning biomass in power plants remains a limited market in industrialised countries;
- in developing countries there is still room for efficiency improvements in biomass burners;
- there is a great potential in upgrading biomass into fuels that can be used in more traditional end use technologies;
- there is a need to develop new harvesting and conversion technologies for energy crops;
- the combination of biofuels with fuel cells could considerably reduce CO₂ emissions in the transport sector; and
- agriculture has taken thousands of years to develop plants that are especially suitable for food. There is immense potential in developing plants that are especially suitable as sources of energy.

Our recommendations are:

- modern bioenergy has large potential, both globally and for Denmark, but more R&D is needed;
- Denmark has a long tradition of agriculture, highly-qualified farmers and a leading industrial position in biotechnology, pharmacy, plant breeding, seed production, energy technologies and renewable energy. Together, these factors give Denmark the opportunity to become the first mover on most key issues in modern bioenergy;
- to exploit these advantages, we deem it of utmost importance that Danish research institutions establish cross-institutional research platforms and co-operative interdisciplinary projects. Such projects should include as stakeholders politicians, industrialists and venture capitalists. In particular, politicians must contribute by setting out the way for bioenergy, and supporting the transition from basic research to competitive technologies ready to enter the market.

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Role of biomass in global energy supply

GUSTAVO BEST, FAO, ROME & JOHN CHRISTENSEN, RISØ NATIONAL LABORATORY

Bioenergy resources: an introduction

Bioenergy is energy of biological and renewable origin, normally in the form of purpose-grown energy crops or by-products from agriculture, forestry or fisheries. Examples of bioenergy resources are fuel wood, charcoal, sugar bagasse, sweet sorghum stocks, livestock manure, biogas, microbial biomass and algae.

Biomass provides approximately 11–14% of the world's energy (IEA, UNDP, WEC), but there are significant differences between industrialised and developing countries.

In many developing countries biomass is the most important energy source. As a global average, biomass provides approximately 35% of developing countries' energy (WEC, UNDP), but there are large regional differences. Many sub-Saharan African countries, for instance, depend on biomass for up to 90% of their energy, indicating that they have little in the way of industry or other modern activities.

The main sources of biomass in developing countries are traditional wood fuels, either collected and used in a non-commercial way or bought in local markets as firewood or charcoal.

In industrialised countries, biofuels have for a long time been considered as old-fashioned because of their bulky nature and low energy content compared to fossil fuels. In the last decade, however, interest in bioenergy has increased. Reasons for this include:

- Growing concern about climate change – biofuels can be carbon-neutral if they are produced in a sustainable way;

- Technological advances in biomass conversion, combined with significant changes in energy markets;
- Biofuels have the unique characteristic of being the only sources of renewable energy that are available in gaseous, liquid and solid states;
- Increasing focus on security of energy supply; and
- Increasing interest in renewable energy generally.

So while many developing countries will aim at reducing dependence on traditional bioenergy fuels as part of policies to improve access to modern energy services, the global trend is expected to focus on how to increase the share of modern bioenergy in the global energy mix.

Examples of current bioenergy use in industrialised countries are the USA (4%), Sweden (17%) and Finland (20%) (WEC). Data on bioenergy resources and utilisation is generally uncertain because of the very diverse and dispersed nature of the resources. In most statistics, bioenergy resources are usually classified as either animal manure or plant biomass, the latter including municipal and other solid waste.

Bioenergy could in principle provide all the world's energy requirements, but its real technical and economic potential is much lower. The WEC Survey of Energy Resources (WEC 2001) estimates that bioenergy could theoretically provide 2900 EJ/y, but that technical and economic factors limit its current practical potential to just 270 EJ/y. Current use of bioenergy is estimated at around 55 EJ/y.

Figure 2 shows the potential and current use of bioenergy by region, based on data from Kaltschmitt. Even with the current resource base, it is clear that the practi-

Table 1. Types of plant biomass. Source: UNDP, 2000.

Woody biomass	Non-woody biomass	Processed waste	Processed fuels
Trees Shrubs and scrub Bushes such as coffee and tea Sweepings from forest floor Bamboo Palms	Energy crops such as sugar cane Cereal straw Cotton, cassava, tobacco stems and roots (partly woody) Grass Bananas and plantains Soft stems, such as those of pulses and potatoes Swamp and water plants	Cereal husks and cobs Bagasse Wastes from pineapple and other fruits Plant oil cake Sawmill wastes Industrial wood bark and logging wastes Black liquor from pulp mills Municipal waste	Charcoal (wood and residues) Briquetted or densified biomass Methanol and ethanol (wood alcohol) Plant oils such as palm, rapeseed (canola) and sunflower Producer gas Biogas

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cal potential of bioenergy is much greater than its current exploitation. Obstacles to greater use of bioenergy include poor matching between demand and resources, and high costs compared to other energy sources.

Projections by the WEC, WEA and IPCC estimate that by 2050 bioenergy could supply a maximum of 250–450 EJ/y, representing around a quarter of global final energy demand. This is consistent with Figure 2, which puts the technological potential of bioenergy at 25–30% of global energy demand.

Land availability

Growing biomass for energy production on a significant scale consumes both land and labour. Land use in particular is a key issue in the production of bioenergy resources, because using land for energy crops means that less land is available to grow food.

It is imperative to ensure that sufficient cropland is available to produce food for the world's expanding population, taking into consideration that biomass energy can help enhance development and food production.

Studies by the FAO and others point to significant reserves of potential cropland, but these resources are not distributed where they will be needed most if present predictions about population growth and competition for land use hold true.

In the industrialised countries, much of the land being removed from agricultural production could profitably and responsibly be used for energy production, because of the associated benefits of such land use. The EC's "set-aside" policy, which encourages farmers to keep part of

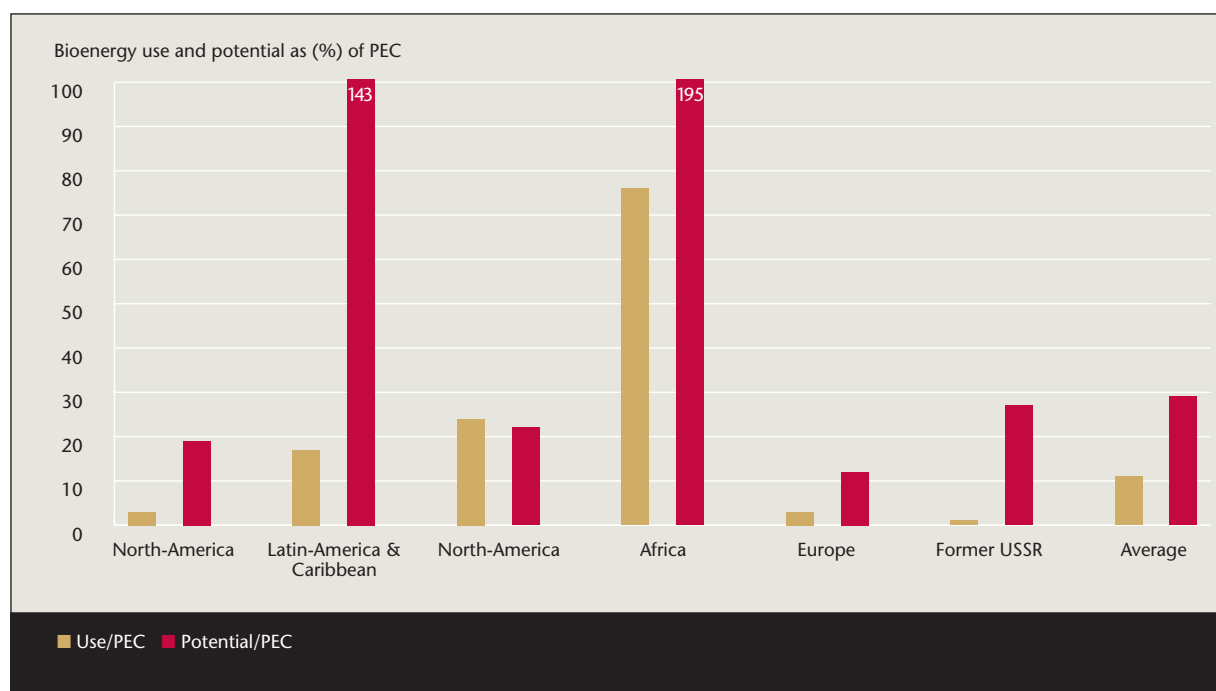
their land fallow, and similar schemes in other countries such as the US are making significant areas of land available. Growing biomass crops on this land could help to re-invigorate rural economies, as well as providing bioenergy and its associated environmental benefits.

In the non-industrialised world, land availability varies between regions and between countries. Some Asian countries appear to have no, or almost no, spare land that could be used for bioenergy. Even in these countries, however, strategies such as agroforestry, efficient energy conversion technologies and the use of agricultural wastes could create significant amounts of bioenergy. Latin America, much of Africa, and several forest-rich countries in Asia have large areas which could be used for bioenergy, given the right long-term policies.

In many developing countries, food and fuel production can be integrated in complementary land use systems. In fact, at the small to medium scale (100 kW–1 MW), agricultural residues and non-arable land can supply villagers' energy needs for domestic water, irrigation, lighting and cooking. Irrigation can greatly increase crop yields, so the implication is that at this scale the use of indigenous biofuels does not need to consume extra land resources. The production of excess biomass can be converted to higher value energy products e.g. charcoal, electricity or synthetic biofuels, which can be sold on the open market. Firewood and charcoal are already significant income sources in rural areas.

At the larger MW scale, land use conflicts could occur where dedicated energy plantations are to supply a central conversion facility i.e. where a bioenergy market is

Figure 2. Technical potential and use of biomass as a percentage of primary energy consumption (PEC) from fossil fuels + hydropower (Based on data from Kaltschmitt 2001).



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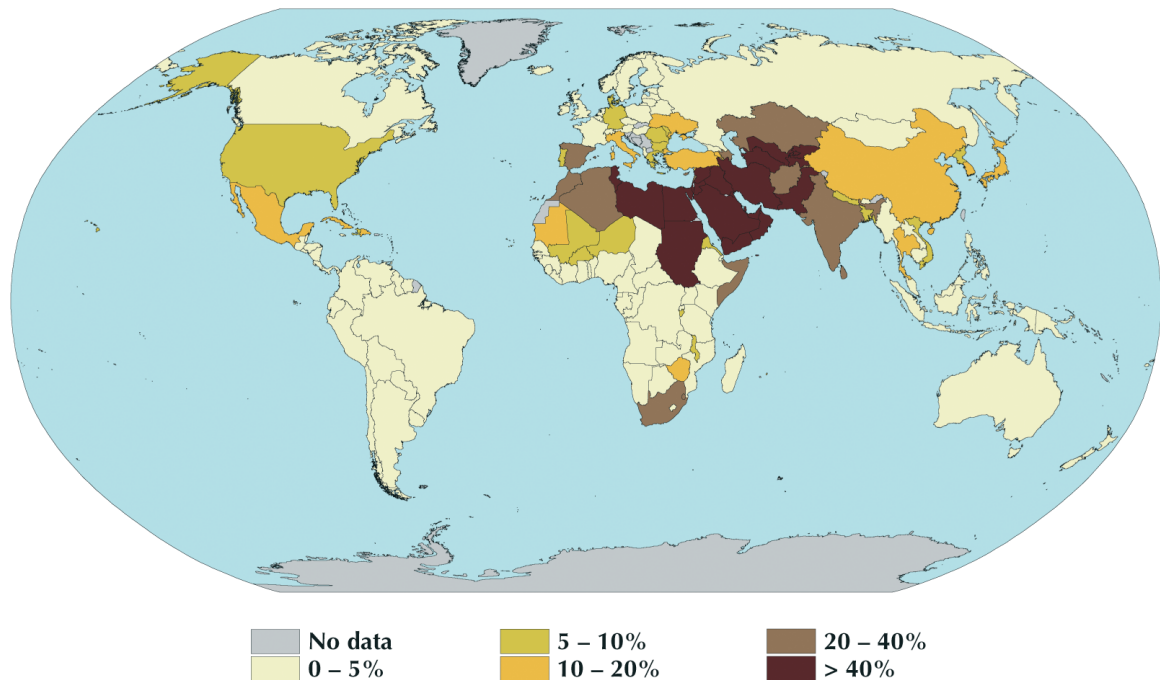


Figure 3. Agricultural water withdrawals: FAO (2003): Agriculture, food and water. A contribution to the World Water Development report. FAO, Rome

stimulated. Since biomass is a low energy density fuel, high transport costs require that the conversion facility secure supplies from as close to the plant as possible. Thus, measures to protect the small farmer near to such a plant may be necessary. However, concerns must also be measured against the benefits accrued by such a plant i.e. increased rural employment (at all skill levels), a secure market for agricultural products and the provision of cheap indigenous supplies of energy.

Bioenergy production can be a way to rehabilitate marginal and degraded land and bring it back into profitable use. This will only happen, however, if it is supported by policy. Without such policy, there is a danger that bioenergy producers will seek good land, where yields are higher, and so compete directly with food production.

Water restrictions

One in five developing countries will face water shortages by 2030. The biggest consumer of water is agriculture, which accounts for around 70% of all freshwater withdrawals worldwide. With a growing world population, agriculture will face more competition from industrial and domestic water users. As a result, agriculture will have to use water more efficiently.

Figure 3 shows agricultural water withdrawals by region as a percentage of water available, and so indicates the level of “stress” caused by current agricultural practices. If bioenergy resources are to meet their full potential, they will have to match the water consumption of other crops in the same region.

Wood, the traditional fuel

Lack of access to convenient and efficient energy is a major barrier to achieving meaningful and long-lasting solutions to poverty. Access to energy is essential in alleviating poverty and achieving sustainable development goals, because it supports strategies for improving employment, education, water supply, public health, local self-sufficiency and a host of other development benefits.

Fuel wood and charcoal are the dominant sources of energy for about half the world’s population. In many countries they also constitute the major forest products. Two to three billion people rely on wood for their primary energy needs and to provide a wide range of other essential goods and services.

For many of these people, wood is far from being a clean and efficient energy source, it is simply their only affordable option. Compared to conventional fossil fuels, wood-fuel and charcoal have low calorific values and are difficult to handle, expensive to transport over long distances and considered dirty in most residential contexts. In many cases, the harvesting of wood-fuels also causes deforestation and loss of vegetation cover.

These negative perceptions are not easily changed, and they restrict the options open to policymakers. This is despite the fact that several countries, both industrialised and developing, have shown that many of the drawbacks can be overcome by using the right technology.

In fact, it is often not understood that appropriate wood-based energy systems can contribute significantly to sus-

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tainable development, particularly in the poorer areas of developing countries. Wood fuels have some advantages over other energy sources:

- They contribute to poverty reduction in developing countries;
- They meet energy needs at all times, without expensive conversion devices;
- They can deliver energy in all the forms that people need (liquid and gaseous fuels, heat and electricity);
- They are CO₂-neutral, and can even act as carbon sinks; and
- They help to restore unproductive and degraded lands, increasing biodiversity, soil fertility and water retention.

Wood fuels usually form part of larger multi purpose systems within forests or agricultural areas. These systems also provide non-wood forest products, reservoirs of biodiversity, traditional medicines and shelter from the wind and sun, all at little or no cost to the world's poorest people. Moreover, most of the added value from village-scale bioenergy systems is retained locally and helps to reduce poverty.

But although wood fuels are widely available and affordable in rural areas of most developing countries, many resources still remain untapped. For wood energy to fulfil its potential as an instrument for sustainable development, a series of technological, institutional, economic and social challenges need to be addressed.

Fuel of the Future

With the traditional association of bioenergy as old fashioned and for the poor, the recent interest in biomass resources has invented a new term "modern bioenergy" which covers a number of technological areas from combustion at domestic, industrial or power plant scale, gasification, hydrolysis, pyrolysis, extraction, digestion etc. Most of these technologies have been available for decades but recent advances in performance have made them economically interesting in view of the resource potential and the possibility of improving environmental performance often along with local employment opportunities. Details concerning individual bioenergy conversion technologies are presented in chapter 5.

Driving forces and practical limitations

Two trends emerge from the discussions above:

- a. Developing countries will in general aim to reduce their dependence on traditional bioenergy as part of their development strategies. The relative share of bioenergy in the energy balance will therefore go down, though the number of people depending on traditional bioenergy will probably remain constant, with corresponding consequences for health and resources.
- b. Industrialised countries, plus a number of developing

countries, will aim to increase their use of modern bioenergy technologies.

Practical limits to bioenergy expansion

Practical limits to bioenergy expansion are set by factors including:

- Resource potential and distribution (as discussed in the Introduction);
- Technological development state of the biomass conversion technologies;
- Costs of technologies and resources;
- Lack of social and organisational structures for fuel supply;
- Public acceptability; and
- Land-use and environmental aspects.

Most of these barriers to the increased use of bioenergy can be overcome through dedicated interventions by both public- and private-sector entities, focusing on:

- Developing and deploying cost-effective conversion technologies;
- Developing and implementing improved dedicated bioenergy crop production systems;
- Establishing bioenergy markets and organisational structures to transport and deliver bioenergy resources and products; and
- Valuing the environmental benefits to society, such as on the carbon balance.

Driving forces to support these activities will be:

- Security of energy supply, which can be increased by using domestic resources;
- Employment and land-use aspects (both for and against the increased use of biofuels);
- Global concerns about climate change; and
- Local concerns about health issues related to burning biofuels indoors.

All of these driving forces in support of biofuels require targeted policy interventions to ensure that the social benefits of increased bioenergy use are properly reflected in the energy markets. In some cases "smart" subsidy schemes may even be needed to ensure that new bioenergy resources and technologies get a level playing field in established energy markets.

A concrete example of a large-scale bioenergy programme is Brazil's PRO-ALCOOL, in which ethanol from sugar cane bagasse is used as a transport fuel. In 1999 Brazil produced and used about 13 billion litres of ethanol in this way (UNDP, 2000).

The PRO-ALCOOL programme was launched in 1975 as a response to the oil crises. In spite of mixed economic results it has been a technical success, and has provided both social and environmental benefits.

The cost of producing the ethanol is equivalent to an oil price of around USD 30 per barrel. When oil prices are

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below this level, the country must pay to produce fuel that could be imported more cheaply as oil.

The beneficial effects of lowering imports by USD 20–30 billion, creating (directly and indirectly) almost a million jobs, cutting air pollution in urban areas and reducing energy-related carbon emissions by 15–20% can be offset against this.

Specific national circumstances mean that it may not be possible to replicate the Brazilian example directly. The PRO-ALCOOL programme does show, however, that good policymaking in response to the driving forces mentioned above can create effective bioenergy solutions. The programme has contributed significantly to overcoming the technological barriers to the wider use of ethanol, not just in Brazil but also worldwide.

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Trends and perspectives in bioenergy supply in Denmark

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Introduction

Energy security and environmental protection have been the objectives of Danish energy policy over the last few decades.

Energy security was the main driving force for several years after the energy crisis of 1973–4. The idea was to make Denmark less dependent on foreign energy, especially imported oil, by adopting multiple energy sources, especially natural gas, and developing new “alternative” energy sources.

Support programmes and tax incentives were launched to promote the development of renewable energy sources, including bioenergy, wind power and CHP, and of systems to increase energy efficiency and improve supply security for Denmark's own oil and gas.

In bioenergy, the most important factor was a political agreement in 1993 which obliged large power plants to burn 1.2 million t/y of straw and 0.2 million t/y of wood before 2000. This was followed by a decision to convert a number of district heating plants to biofuels and CHP. In the past few years the political focus has shifted towards opening up the natural gas and power markets as part of Denmark's transition to a free market within the European Union. Support for energy R&D has been much reduced since the end of 2001.

Since the 1992 Rio “Earth Summit”, however, growing concern for the global environment has replaced the old agenda of supply security with a new mandate to maintain and enlarge Denmark's role as a pioneer in sustainable development.

As a result, Danish commitment to the Kyoto Protocol has become a strong driving force for energy and environmental policy, resulting in various energy plans with specific targets for greenhouse gas reductions and ways of reaching these targets. In support of this, the Danish Parliament has decided that no new coal-fired power plants will be built. Parliament has also decided that nuclear fission, which by its nature is CO₂-neutral, will not be used for power production in Denmark.

Bioenergy

Danish energy production based on biomass from agriculture and forestry, including biogas, made up around 45% of the country's total renewable energy production in 2001 (Table 2). Straw and firewood are the most important biofuels, followed by industrial wood waste.

Wood fuel in Denmark is available as industrial wood waste (raw or as wood pellets), forest chips, firewood and a very small amount of coppice willow from short-rotation forestry. Firewood, and to an increasing extent wood pellets, are mainly used to heat private houses. Most industrial wood waste is used for industrial heating, while wood chips are primarily used in CHP plants. Wood as an energy resource contributes 25.5 PJ (Table 2), equivalent to approximately 0.6 million tones of oil. Table 2 illustrates the distribution among the individual wood fuels, but does not include wood waste in the form of broken or worn-out furniture, paper etc.

Table 2. Bioenergy production from agriculture and forestry (2001)

Fuel type		Resource contribution (PJ)
Non-wood	Straw	13.7
	Urban waste	33.0
	Biogas	3.0
Wood	Firewood	12.6
	Industrial wood waste	7.2
	Wood chips	3.2 (6.5 in 2002)
	Wood pellets	2.5 (4 in 2002)
Total		75.2 (approximately 80.0 in 2002)

Note: 1 PJ is equivalent to the lower calorific value of 23,810 t of oil. Source: Energistatistik 2001; Danish Energy Agency.

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Since the late 1990s there has been an increasing international trade in wood chips and wood pellets, and Denmark now imports substantial amounts of these. Total Danish consumption of wood is approximately 8 million t/y, of which 6 million t/y is imported and Danish forests supply the rest. The intention is that most of this wood ends up as fuel, either directly or after having been used for other purposes first. In the latter case, however, national statistics class the wood simply as “waste”, making it hard to distinguish from other kinds of waste. Under the 1993 “bioenergy agreement” two new CHP plants started production in 2002, one using 200,000 t/y of wood chips and the other 150,000 t/y of straw. Only a very small part of Denmark’s approximately 30 million t/y of animal manure is currently used to produce biogas. A number of relatively large on-farm biogas plants started production in 2002, the last centralised biogas plant having been put into production in 1998. Changes in subsidies for green electricity produced on new plants built after 2002 have put an economic halt to new biogas plants. However, the recent agreement for subsidies for electricity from new biogas plants has opened up for a number of new biogas initiatives.

The Danish bioenergy industry

The bioenergy technologies currently most developed in Denmark are those for biogas production (Table 3). The basic raw material is animal manure, of which Danish farms produce 34.1 million t/y (including 27.0 million t/y of slurry). Green Farm Energy A/S has developed an advanced biogas plant that runs on manure, supplemented with other agricultural waste products containing less water, such as straw or future energy crops. The plant also removes nitrogen and phosphate from its waste stream, thus solving the problem of how to stop these two nutrients polluting watercourses.

Another novel concept is to use manure and wheat straw in a combined process that yields bioethanol as well as biogas (Chapter 6.4). Reference 2 also lists a large number of manufacturers and suppliers of wood-fired boilers.

Rapeseed is the only oilseed crop currently grown by Danish farmers. Several mills are now refining cold-pressed rapeseed oil so that it can be used in heating systems. The potential for using rapeseed oil as a source of biodiesel has not yet been fully explored in Denmark. Emmelev Mølle is the only producer of rapeseed oil methyl esters (RME, or biodiesel). Due to lack of national tax exemptions for liquid biofuels most of this is exported to Sweden and Germany instead of being used in Denmark. When biomass such as wood and straw burns, a number of chemical processes convert the carbonaceous material into a mixture of gases which are subsequently combusted. It is possible to use the energy contained in the biomass more efficiently by separating the processes of gasification and combustion. New two-stage gasifier (Table 3) plants use fixed-bed or fluidised-bed reactors to produce a mixture of carbon monoxide and hydrogen, which can then be burned either alone or combined with gas from other sources. A challenge for gasification technology is to remove the corrosive ash created by the high levels of chloride and potassium present in plant biomass or high molecular tars and hydrocarbons from the pyrolysis and gasification process. Ashes from biomass only, are recycled to agriculture and forestry. Denmark’s forest area of approximately 0.5 million ha supplies an increasing amount of firewood and forest chips. In the light of the Government’s plan to double this area of forest, Denmark’s total wood fuel resources will increase in the years to come. Afforestation takes place on agricultural land and will therefore result in a

Table 3. Bioenergy industry in Denmark.

Company	Technology type
Bioscan A/S	Biogas
GasCon	Biogas
Gosmer Smeden	On-farm biogas
Dansk Biogas A/S	Biogas
Green Farm Energy A/S	Biogas
Lundsby Bioenergi	Biogas
Emmelev Mølle	RME, biodiesel
Cowi with DTU / Vølund	Gasification
Danish Fluid Bed Technology	Gasification
Hollensen	Gasification
Carbona / Skanska	Gasification

Source: this manuscript.

4

proportional decrease in the straw and energy crop potential.

Environment

As a small country, Denmark is heavily influenced by international agreements on energy and environmental issues, and the increasing internationalisation of markets. To avoid being swamped by outside forces, Denmark must therefore secure the greatest possible influence in international affairs concerning energy and the environment. This will help the country achieve its goals and create the best conditions for its domestic environment and economy.

The EU Directive has set as an “indicative goal” that by 2010, 29% of Denmark’s electricity should be produced from renewable sources, including biomass and bio-waste. Agriculture and forestry provides 47 PJ in 2002 and urban waste is predicted to contribute with constant amount of 33 PJ.

Forest chips result from first and second thinning, from harvesting over-mature and partly-dying pine plantations, and from tops following clear-cutting. Wood chips have become even more important as a fuel over the two last decades, and their significance is underlined by the Danish national obligation to reduce CO₂ emissions.

The production of biogas from manure will also affect the environment. In particular, the ability of large on-farm biogas plants to remove nitrogen and phosphate will reduce the quantities of these nutrients polluting watercourses and coastal areas. Instead, farmers will be able to recycle the nitrogen and phosphate for crop production.

What can be done?

In previous decades Danish energy policy was marked by strong public involvement at every stage and a pioneer-

ing approach towards global sustainable development. This has been replaced by a new balance between general economic growth and the development of energy technology. The priority in energy policy is now liberalisation, with the aim of meeting Denmark’s international environmental commitments and at the same time expanding the economy.

The Kyoto Protocol’s flexible mechanism shall be used as an integrated part of the Danish climate change policy in order to fulfil the Kyoto commitment. The Danish Government has started a process in order to analyse how climate target in Denmark is to be obtained most cost effectively. The use of the Mechanism plays a central role in the planning of the process. The planning is carried out in co-operation between the Ministry of Finance, Environment, Foreign Affairs, Taxation and the Ministry of Economic and Business Affairs (Energy) to assist the energy industry in implementation of the JI and the CDM tools. The JI projects are expected to be launched primarily in the Eastern Europe while CDM projects are to be carried out in the developing countries.

Future bioenergy resources

Danish bioenergy from agriculture and forestry is currently based mainly on waste materials such as straw, waste from the wood industry and forest thinnings. Under the revised bioenergy agreement, by the end of 2004 the electricity companies are obliged to use 1.4 million t/y of biomass, including 930,000 t/y of straw. Agriculture, forestry and the wood industry can easily supply these quantities of biomass.

Given the present political strategies for energy and the environment, it is difficult to foresee any substantial increase in the demand for solid biofuels from agriculture beyond 2004. At present there is no tax exemptions or subsidies for liquid biofuels and the future national

Table 4. Estimated biomass resources from agriculture for energy purposes, 2015. Based on Gylling et al. 2001.

	Unit	Scenario			
		2000 Current	2015 Reference	2015 Environmental	2015 Market
Total straw production	tonne	6,484,000	5,857,000	4,840,000	6,758,000
Available straw for energy purposes	tonne	2,663,000	2,445,000	1,414,000	3,494,000
	PJ	37.4	34.3	19.8	49.0
Available area for energy crops	ha	186,000	168,800	160,000*	85,000
Potential energy production	PJ	27.9	25.3	24.0	12.8
Total potential straw and energy crops	PJ	65.3	59.6	43.8	61.8
* 85,000 hectares ESA – set-aside. + 75,000 hectares set-aside					

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politics is not yet known. If demand were to increase, however, current biofuel resources would soon be fully utilised. The logical next step would be to grow dedicated energy crops, though under the present Common Agricultural Policy (CAP) this would only be economic on set-aside land.

A study by the Danish Research Institute of Food Economics estimates potential production of biomass for energy in the range 44–62 PJ/y, depending on developments in the framework conditions for Danish agriculture (Table 4).

The study outlines three different agricultural scenarios up to 2015. The first scenario is a reference case in which current trends are simply extrapolated. The “environmental” scenario proposes a higher degree of environmental awareness, while the “market” scenario imagines a future in which agriculture becomes more competitive in economic terms.

The estimate of total biomass available for energy production is based on the assumption that set-aside land is used to grow a mixture of energy crops; whole crop wheat and triticale, plus willow coppice. The average annual yield is estimated at 9 t/ha of dry matter. The reference and market scenarios estimate the amount of energy available from biomass at 59.6 PJ and 61.8 PJ respectively, though the market scenario includes about 40% more straw because grain production is higher. The environmental scenario yields only 43.8 PJ of bioenergy, mainly because grain production is lower.

Straw and energy crops (whole crop grain, willow and *Miscanthus*) are to a large extent interchangeable in large multi-fuel burners (Gylling 2001), but differences in storage characteristics need to be taken into account when setting up the biofuel production chain in order to secure an economic efficient all year supply.

Fuel pellets seem to be an expanding market. Wood pellets currently account for almost the entire market, but a recent Danish study (Nikolaisen 2002) found that fuel pellets made from mixed biomass sources can provide

the same quality as wood pellets, as long as the right ingredients and additives are used.

Most firewood comes from thinning and clear-cutting of hardwood stands, in the form of smaller trees, tops and branches. Official statistics show that Danish forestry produces approximately 450,000 m³/y (solid volume) of firewood, but this does not take into account firewood taken from gardens and parks.

There have been three assessments of forest fuel resources in Denmark. Table 5 shows predictions for fuel-wood resources (forest chips plus forest firewood) taken from the most recent of these assessments (Nord-Larsen & Heding, 2003), which extrapolates from the current national forest inventory using models for forest growth and yield. The figures cover three ten-year periods (2000–2009, 2010–2019 and 2020–2029), each under three scenarios in which utilisation of forest resources becomes progressively more intense.

The three scenarios are:

1. Whole-tree chips from early thinning and from final felling of over-mature pine.
2. In addition to Scenario 1, forest chips from branches and tops harvested during final felling.
3. In addition to Scenario 2, forest chips from tops and branches harvested during later thinning.

Under all three scenarios, potential production of forest chips exceeds the current figure by a factor of 1.5–2.

Research

Research on wood fuels has changed direction over the years. In the 1980s the focus was on harvesting techniques and long-term storage. In the 1990s emphasis changed to the physical characterisation of wood chips, their storage properties, and how to optimise silvicultural regimes to produce more chipping material.

Current research topics include reducing the harmful effects of mould and understanding the nutrient balances associated with intensive chip harvesting from

Table 5. Danish fuel-wood resources for three scenarios over the next 30 years. Source: Nord-Larsen & Heding, 2003.

Scenario	Fuel-wood production	Time period		
		2000–2009	2010–2019	2020–2029
1	Volume (million m ³ solid volume/y)	0.9–1.3	0.9–1.3	0.9–1.3
	Energy (PJ/y)	8–11	8–11	8–11
2	Volume (million m ³ solid volume/y)	1.1–1.5	1.1–1.5	1.2–1.6
	Energy (PJ/y)	9–12	9–12	9–13
3	Volume (million m ³ solid volume/y)	1.3–1.7	1.3–1.7	1.4–1.8
	Energy (PJ/y)	11–14	9–14	9–15

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whole trees. More use of forest fuels means more wood ash, and another research topic is how ash can be returned to the forest floor – a disposal route that is hindered by current regulations. Yet another research area is how to improve the performance of the wood fuel supply chain, which at the moment is very tight.

Future R&D should also aim to create new plant strains with high energy contents and other characteristics to make them suitable as biofuels. New chemical and biological transformations, as well as improvements to existing separation and concentration processes, are needed for the production of bioethanol, biodiesel and hydrogen and other biofuels.

Danish farmers will continue to grow rapeseed if for no

other reason than its advantages in crop rotation, so a significant and predictable amount of rapeseed oil can be expected. To make it ideal for biodiesel (RME) production, however, rapeseed needs to be developed so that its oil is more resistant to high temperatures and oxidation. Other technical advances would allow rapeseed to be used to create biolubricants as well.

To meet these goals a multitude of instruments are used by Danish R&D connecting public and private sector. The funding is provided by the public, national as well as EU and for some specialized issues by DOE. Private investors show increasing interest in this field to develop local industry which address European agrofuels challenges, because the Danish market is limited in size.

5

Emerging and future bioenergy technologies

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Introduction

In recent years biotechnology has featured in most “top ten” lists of emerging technologies. Energy supply based on biomass occupies a similar position in the list of emerging technologies for renewable energy, and yet the interface between biotechnology and power generation remains in most cases wide open for development.

There is no generally acknowledged definition of the term “emerging technologies”. A recent book from Wharton Business School defines emerging technologies as “*science based innovations that have the potential to create a new industry or transform an existing one*”¹. The authors distinguish between two kinds of emerging technologies: discontinuous and evolutionary.

Discontinuous technologies derive from radical science-based innovations, while evolutionary technologies arise at the junctions of research streams that were previously separate. The latter definition applies especially to biomass-based energy technologies, where enormous synergies could be gained from joining together disconnected areas of scientific investigation.

One of the biggest challenges to the continuing use of fossil fuels is associated with global warming caused by CO₂ emissions. This report concentrates on biomass-based energy technologies, but biotechnology could also contribute to the development of CO₂-neutral power generation systems based on fossil fuels. There are essentially two distinct areas where biotechnology can contribute:

a) The area of traditional biotechnology, so-called white

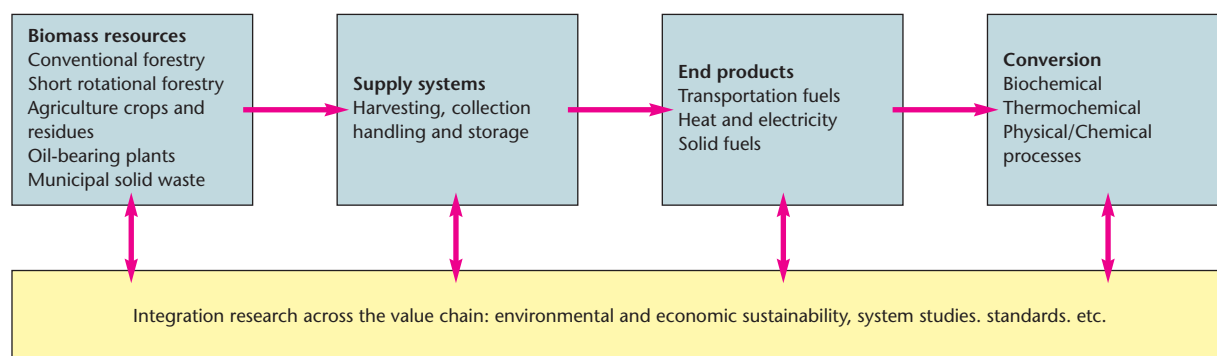
biotechnology, is related to the technical use of fermentation processes or enzymes in downstream processes of biomass conversion. This is firmly established and an integral part of the processes described below.

b) The area of green biotechnology is related to the genetic engineering of plants in order to tailor biomass with respect to their efficiency as energy resource. This area is only emerging and has only been explored superficially. To date almost only biomass as energy source has been investigated that was available from traditional cropping or forestry systems. The challenge is now to establish small scale prediction systems allowing to establish structure-function relationships between biomass composition and its convertibility in energy conversion systems, in order to explore a broad range of generated biodiversity also in energy cropping systems.

The IEA has set up a useful taxonomy setting out the different fields of research whose integration will help create sustainable biomass-based energy technologies (Figure 4). The field of *biomass resources* is mainly concerned with optimising existing production systems for maximum energy output. Here especially, green biotechnology will provide tools to broaden genetic variability and develop novel feedstocks for energy production systems. *Supply systems* represent the largest technical challenge in optimising bioenergy generation and use, as supply is

¹ Day and Shoemaker, 2000; 2

Figure 4. The IEA taxonomy shows the different fields of research whose integration will aid the development of sustainable biomass-based energy technologies.



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always related to energy consumption and may well be influenced by the development of decentralised power generation systems. *Conversion* depends in part on the development of white biotechnologies to establish commercially-feasible energy production systems, whereas research into *end products* is oriented more towards engineering and the optimisation of plant and machinery for use with biomass.

Current developments

Table 6 uses the IEA taxonomy to summarise the major emerging and future technologies in bioenergy. Emerging technologies are defined as above, while future technologies are those that will take more than ten years to reach the market.

"Bioenergy" is sometimes thought of as old-fashioned

and for poor people. To distinguish modern technology from traditional practices, the term "modern bioenergy" is sometimes used to cover more sophisticated combustion systems (at domestic, industrial or power-plant scale), gasification, hydrolysis, pyrolysis, extraction and digestion technologies.

Most of these technologies have been available for decades, but have not been economic. Recent advances in performance have made them much more attractive, especially in view of their ability to improve the environment and create jobs at the same time as making use of available energy resources.

There are five fundamental forms of bioenergy use:

1. "Traditional domestic" use in developing countries, burning firewood, charcoal or agricultural waste for household cooking (e.g. the "three stone fire"), light-

Table 6. Emerging and future technologies in bioenergy.

Stage	Emerging technologies	Future technologies
Biomass resources	New energy crops New oilseed crops Bio-waste management	Bioengineering of new energy plants Development of low-energy agricultural production systems Aquatic biomass (algae) IT methods in land and biological systems management
Supply systems	Use of new agro-machinery Biomass densification Other simple pretreatments (e.g. leaching) Logistics of supply chains	Biorefining Biotech-based quality monitoring throughout the whole procurement chain IT tools for supply chain modelling and optimal management
Conversion	Advanced combustion Co-combustion Gasification Pyrolysis Bioethanol from sugar and starch Bioethanol from lignocellulosic material Biodiesel from vegetable oils Advanced anaerobic digestion	Biohydrogen (hydrogen from bioconversion of biomass) Plasma-based conversions Advanced bioconversion schemes Other novel conversion pathways (e.g. electrochemical) Novel schemes for down-stream processing (e.g. of pyrolytic liquids or synthetic FT-biofuels)
End products	Bioheat Bioelectricity Transport biofuels Upgraded solid biofuels	Use of hydrogen in fuel cells Use of FT-biofuels in new motor-concepts e. g. CCS (Combined Combustion Systems) New bio-products (biotech) Complex, multi-product systems (IT) CO ₂ sequestration; other new end-use "cultures" (e.g., user-friendliness, "closed cycle")
System integration	Normalisation and standards Best practices Economic/ecological modelling and optimisation	IT-based management Socio-technical and cultural design of applications Sustainability based on global as well as local effects

5

ing and space heating. Energy conversion efficiency is generally 5–15%.

2. "Traditional industrial" use for processing tobacco, tea, pig iron, bricks, tiles etc. The biomass feedstock is often regarded as "free", so there is generally little incentive to use it efficiently and energy conversion efficiency is commonly 15% or less.
3. "Modern industrial" use, in which industries are experimenting with technologically-advanced thermal conversion technologies. Expected conversion efficiencies are in the range 30–55%.
4. Newer "chemical conversion" technologies (fuel cells). These are capable of bypassing the entropy-dictated Carnot restriction that limits the conversion efficiencies of thermal conversion units.
5. "Biological conversion" techniques, including anaerobic digestion for biogas production and fermentation for alcohol e. g. from lignocellulosic raw material.

In general, biomass-to-energy conversion technologies have to deal with feedstocks that vary widely in their mass and energy density, size, moisture content and availability. Modern industrial installations therefore often employ hybrid technologies, in which fossil fuels are used to dry and pre-heat the biomass before it is burned, and to maintain production when biomass is unavailable.

Bioenergy conversion technologies

Among the most important bioenergy conversion technologies are:

Direct-combustion processes

Feedstocks for direct combustion are often residues such as woodchips, sawdust, bark, hogfuel, black liquor, bagasse, straw, municipal solid waste (MSW) and wastes from the food industry. Direct-combustion furnaces are used to produce either direct heat or steam.

Co-firing

A modern practice is the co-firing of a fossil-fuel, usually coal, with a bioenergy feedstock. Co-firing has a number of advantages, especially for electricity production. It may be relatively cheap to modify existing fossil-fuel equipment for co-firing, so this can be a cost-effective way to cut fuel bills or meet new emission targets.

Thermochemical processes

Thermochemical processes do not necessarily produce useful energy directly. Instead, they use controlled conditions of temperature and oxygen level to convert the original bioenergy feedstock into more convenient energy carriers such as producer gas, oil or methanol. Compared to the original biomass, these energy carriers either have higher energy densities – and lower transport costs – or more predictable and convenient combustion

characteristics, allowing them to be used in internal combustion engines and gas turbines.

Carbonisation

Combustion is an age-old process optimised for making charcoal. In traditional charcoal-making, wood is placed in mounds or pits, covered with earth to keep out oxygen, and set alight. Modern charcoal processes are more efficient; large-scale industrial production of charcoal in Brazil, for instance, achieves efficiencies of over 30% by weight.

Pyrolysis

Pyrolysis is a step on from carbonisation in which biomass is processed at high temperatures and the absence of oxygen, sometimes at elevated pressure. The shortage of oxygen prevents complete combustion, and instead the biomass is broken down to a mixture of simple molecules (methane, carbon monoxide and hydrogen) known as producer gas. Charcoal, coke and other heavy materials are often produced as residue.

Gasification

With careful control of temperature and oxygen level it is possible to convert virtually all the raw material into gas. Gasification, which is a further development of pyrolysis, takes place in two stages. First, the biomass is partially burned to form producer gas and charcoal. In the second stage, the carbon dioxide and water produced in the first stage are chemically reduced by the charcoal, forming carbon monoxide and hydrogen. The composition of the resulting gas is 18–20% hydrogen, 18–20% carbon monoxide, 2–3% methane, 8–10% carbon dioxide and the rest nitrogen. Gasification requires temperatures of around 800°C or more to minimize the residues of tars and high hydrocarbons in the product gas.

Catalytic liquefaction

Catalytic liquefaction has the potential to produce higher-quality products of greater energy density than are possible with other thermochemical processes. These products should also require less processing to get them into marketable form. Catalytic liquefaction is a low-temperature, high-pressure thermochemical conversion process carried out in the liquid phase. It requires either a catalyst or a high partial pressure of hydrogen. Technical problems have so far limited the applications of this technology but the quality of the products justifies the expenses. Further R&D activities for optimal concepts of these conversion strategies must be applied

Biochemical processes

The use of yeast to produce ethanol is an ancient art. However, in more recent times micro-organisms have become regarded as biochemical "factories" for treating and converting most forms of human-generated organic

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waste. Microbial engineering has encouraged the use of fermentation technologies (aerobic and anaerobic) for the production of energy (biogas) and fertilisers, and for removing unwanted products from water and waste streams.

Anaerobic fermentation

Anaerobic reactors are generally used to make methane-rich biogas from manure (human and animal) and crop residues. Anaerobic digesters of various types are widely distributed throughout China and India. They are ideal for rural areas because they improve sanitation as well as producing fuel and fertiliser. Large digesters are becoming useful in environmental protection applications such as removing nitrates from water supplies.

Methane production in landfills

Anaerobic digestion in landfills is brought about by the microbial decomposition of the organic matter in refuse. Landfill gas is on average 60% methane and 40% carbon dioxide.

Ethanol fermentation

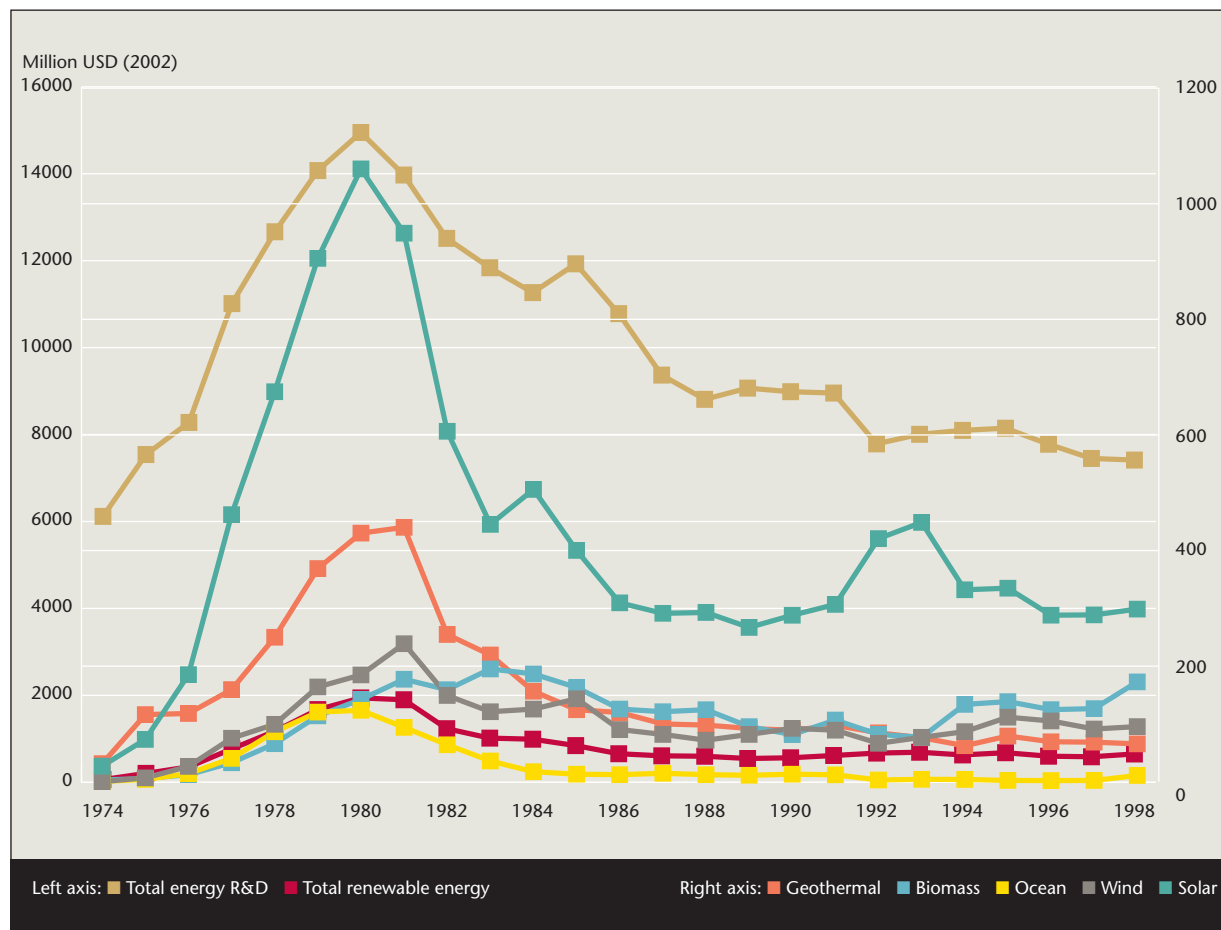
Improvements in fermentation technology have made bioethanol economically competitive, as well as environmentally beneficial, as a petroleum substitute and fuel enhancer. Bioethanol programmes exist in Brazil, Zimbabwe, and the USA.

The commonest bioethanol feedstock in developing countries is sugar cane, due to its high productivity when supplied with sufficient water. Where water availability is limited, sweet sorghum or cassava may be preferred. Other feedstocks include saccharide-rich sugar beet and carbohydrate-rich potatoes, wheat and maize. Recent advances in the use of cellulosic feedstock may allow bioethanol to be made competitively from woody agricultural residues and trees.

Biodiesel

Vegetable oils have been used as fuel in diesel engines for over a century. Whilst it is feasible to run diesel engines on raw vegetable oils, in general these oils must first be

Figure 5. Development in governmental R&D expenditures from 1974 to 1998. Figures are in millions of USD with a 2002 price level. Data downloaded via: <http://www.iea.org/stats/files/rd.htm>



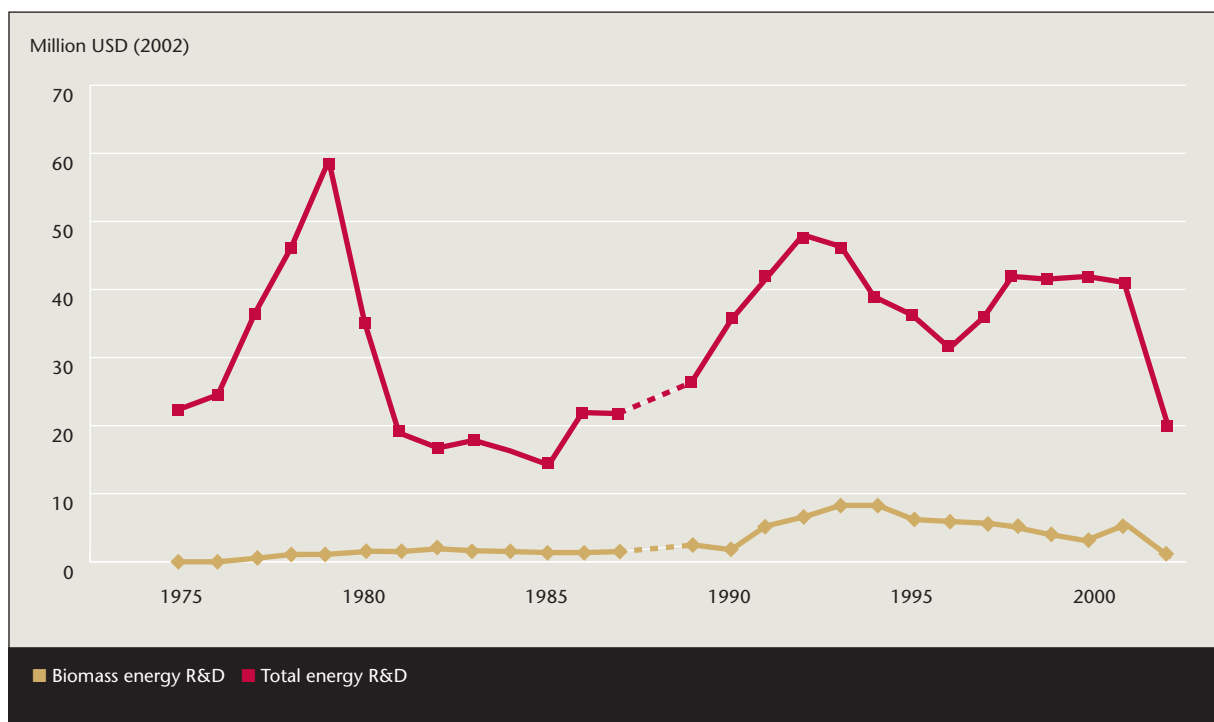


Figure 6 . Development in Danish governmental R&D expenditures from 1975 to 2002. Figures are in millions of USD with a 2002 price level. Data downloaded via: <http://www.iea.org/stats/files/rd.htm>. No figures available for 1988.

chemically transformed so that they more closely resemble petroleum-based diesel.

The raw oil can be obtained from a variety of annual and perennial plant species. Perennials include oil palms, coconut palms, physica nut and Chinese tallow tree. Annuals include sunflower, groundnut, soybean and rapeseed. Many of these plants can produce high yields of oil, with positive energy and carbon balances.

As a rule, most of the emerging biomass technologies are those now receiving R&D funding from government and other sources. Future technologies, on the other hand, depend strongly on interactions between current emerging technologies and generic developments in biotechnology and IT. These interactions can only be reliably achieved by systematically steering biotech and IT research towards bioenergy subjects – a critical task on the research agenda for the next decade. We should also mention the critical role that social and cultural aspects are expected to play in the future of this complex field.

R&D indicators in biomass for energy

Since emerging technologies, on the Wharton definition, are closely related to science-based innovations, it is logical to examine some traditional indicators of research and development activity in biomass energy technologies.

It is well known that global government R&D spending on energy has decreased steadily since its peak at around the time of the second oil embargo in 1979. According to the IEA, total expenditure on government energy R&D in IEA member countries fell by more than half during the 1980s and 1990s, but with relatively large variations between individual countries and between technologies. Biomass-related energy R&D has managed to increase its share of government spending, in both relative and absolute terms, in the last decade or so (Figure 5). The opposite is the case for Denmark where the biomass related governmental R&D has decreased after a peak in early 1990's (Figure 6).

Breakthroughs in energy-related biotechnology do not have to stem from targeted energy research, of course. They can equally well be a consequence of generic research programmes.

6

Bioenergy technologies in global, European and Danish perspective

The following chapter presents the status of R&D in progress for selected bioenergy technologies. Selection is based on evaluation of technologies characterized by a larger research effort and a longer time scale. The presented technologies are assessed with respect to status, trends and perspectives for the technology together with international R&D plans.

Conclusions are drawn for each technology in the form of a simple, graphical overview for the technology. The

overview is based on a qualitative "best estimation" – with the uncertainty this implies – on a time scale presenting the phases of the technology from breakthrough to commercial contribution. Each phase presents some examples of the necessary steps to exploit the potentials of the technology and move it to the next phase all the way to commercial contribution. The last-mentioned phase indicates the point of time when the first units of the technology are for sale on a commercial basis.

6.1

Biomass production in new sustainable multipurpose cropping systems

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Biomass production

This chapter mainly concerns the production of ligno-cellulosic biomass for generating heat and power. To date, such material has been available almost exclusively in the form of surplus or waste biomass from forestry or agriculture. However, as the demand for renewable energy increases to fulfil the ambitious goals of the EU’s White Paper on renewable energy, new ways to increase biomass production from energy crops need to be developed.

Furthermore, there is a general demand within the EU for sustainable crop production characterised by reduced inputs of pesticides and chemical fertilisers, reduced nitrate leaching and increased agro-biodiversity. The challenging possibility now exists of developing new, efficient, energy-crop systems based on these principles. Compared to existing cropping systems, these new systems also have to show a clearly positive energy balance. One obvious place to grow energy crops is on set-aside land – defined by the EU as land that is available for agriculture but not currently used to grow food or fodder crops. Across the EU, set-aside accounts for 10% of the area used for grain or oilseed crops. Denmark has about 200,000 ha of set-aside, which could produce 33 PJ/y (lower heating value) if used for energy crops with an average yield of 10 t/ha dry matter.

Energy crops

Many different crops can produce biofuels for heating, power and transport. The European Energy Crops Overview showed that more than 30 species had been

tested as energy crops (Venendaal et al., 1997). Conventional crops such as wheat, rye, triticale and sweet sorghum have been used as energy crops (Table 7), with the advantage that farmers already know how to grow them. Current thinking, however, is that it is not a good idea to grow grains as dedicated energy crops . The problem is that these crops require higher input and annual ploughing, which leaches nitrates and other nutrients from the soil (Jørgensen & Mortensen, 2000). Instead, much recent research in Denmark and the rest of the EU has looked at perennial energy crops such as willow, poplar, alder, giant reed, *Miscanthus* and cardoon (Jørgensen & Schwarz, 2000).

Compared to traditional crops, the perennials need lower inputs (Venendaal et al., 1997; Jones & Walsh, 2001) and pose much less risk of nutrient leaching (Jørgensen & Mortensen, 2000; Aronsson & Bergström, 2001). Biomass from perennial crops contains lower levels of nutrients, which means more efficient use of nutrient input and better combustion characteristics (Jørgensen & Sander, 1997; Jørgensen & Schelde, 2001).

Promising as the perennial energy crops are, they are still relatively new and do not benefit from the centuries of selection and breeding associated with conventional crops. Much progress in improving yield and quality remains to be made through better breeding and crop management.

Another ‘new’ perennial energy crop, switchgrass, has been studied extensively in the USA. Switchgrass is indigenous to the US prairies, where it is grown to reduce

Table 7. The most popular energy crops in Denmark and the EU (Venendaal et al., 1997). No new inventory of European energy crop area has been done since 1996.

Common name	Annual/perennial	Hectares in Denmark, 2002	Hectares in EU, 1996
Oilseed rape	A	19,973	800,000
Willow	P	834	18,000
Winter wheat, winter rye, triticale, spring barley	A	0	9,400
<i>Miscanthus</i>	P	30	170
Reed canary grass	P	0	4,050
Poplar	P	9	550
Sunflower	A	–	91,000
Sugar beet	A	–	6,250
Hemp	A	–	350

6.1

soil erosion and to create wildlife habitats. More recently, a large research project combining physiology, plant breeding and crop management has shown that switchgrass has a promising future as an energy crop² (Sander et al 1996).

Like *Miscanthus*, switchgrass benefits from the more efficient "C4" photosynthesis compared to the "C3" photosynthesis used by most common crops. Switchgrass is easy to establish from seeds, and varieties suited for different climates are available.³ Switchgrass has recently been tested under European conditions as part of an EU project.

Breeding for productivity and quality

Swedish experience with willow has shown that exploiting the genetic resources of a "new" crop species through careful breeding can create big improvements in a short time. The latest willow varieties commercially available from the breeding company Svalöf Weibull, for example, show yields 63% higher than the reference variety, which itself was the best available when breeding began in 1987.⁴

In other species the genetic pool remains largely untapped. In *Miscanthus*, for example, nine different genotypes showed a 2.4-fold difference in radiation conversion efficiency (the ability of the plant to convert

energy from the sun into dry matter) (Jørgensen et al., 2003a). It is reasonable to assume that in the long term better breeding of *Miscanthus* could double its current yield of biomass.

Willow can be burned in existing wood-fired energy plants, and *Miscanthus* can be used directly in plants designed to burn either straw or wood. In the long term, however, it may be possible to reduce the capital costs of bioenergy plants by taking advantage of the special properties of these new crops.

One example of this relates to the concentration of chloride and potassium salts in biomass. Straw contains a lot of these salts, which can cause corrosion and slagging problems. The need to make power plants from corrosion-resistant materials has increased the cost of energy from straw, at least in Denmark.

Another solution to the corrosion problem is to use crops with a lower salt content (Jørgensen & Sander, 1997). Compared to straw, *Miscanthus* contains lower concentrations of salts, and some varieties are particularly low in salts (Figure 7). Future programmes of breeding or genetic modification could yield *Miscanthus* strains with optimal combustion qualities (Atienza et al, 2003).

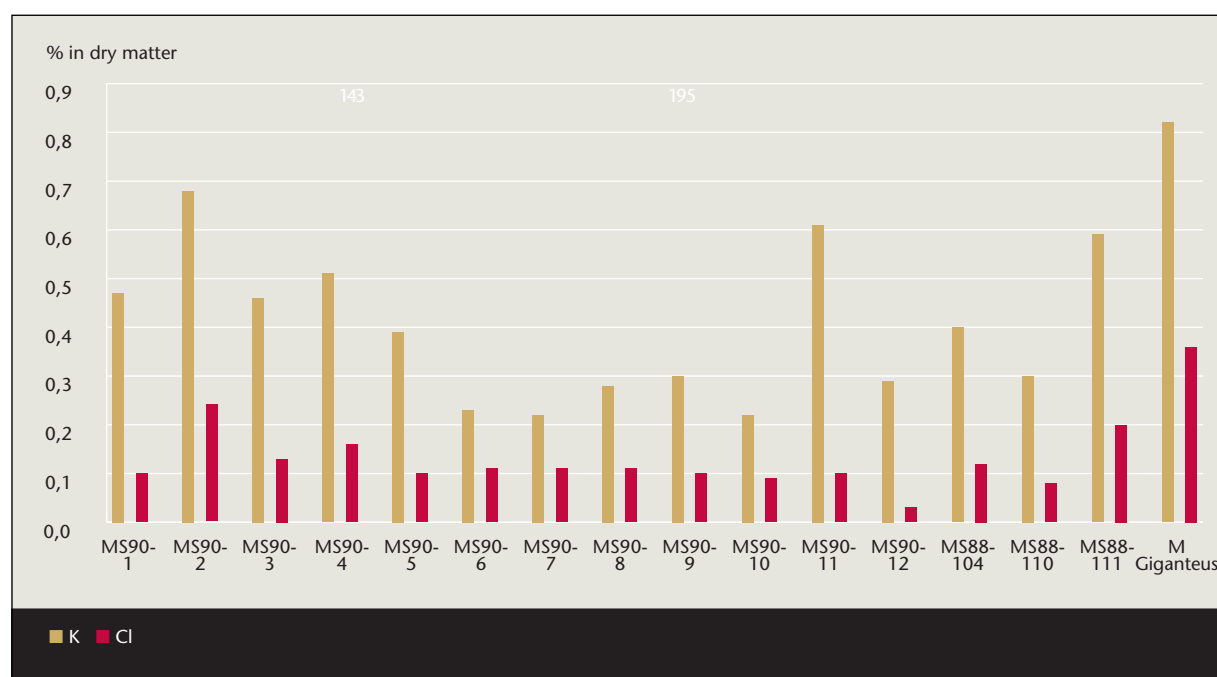
Another way to beat the salt problem may be to convert the biomass into liquid biofuels instead of burning it (section 6.4).

² For details of the potential commercial use of switchgrass in large US bioenergy projects, see for example: www.state.ia.us/dnr/energy/programs/switchgrass/switchgrass.htm and <http://bioenergy.ornl.gov/papers/misc/switgrs.html>

³ see www.switchgrass.nl/index.htm

⁴ www.agrobransle.se

Figure 7. Salt content (potassium and chloride) of 15 *Miscanthus* genotypes grown in Denmark, measured at spring harvest over three years (Jørgensen, 1997). One genotype has just 10% of the chloride content of some other varieties.



6.1

Cropping systems for energy crops

Making use of diversity within a single crop, intercropping of different species and crop rotation are all ways to increase both yields and the efficiency of resource use (Finckh and Wolfe, 1996).

For example, it is well-known that mixtures of cereals generally stabilise yields, reduce losses due to disease, so less fungicide is needed, and buffer abiotic stresses compared to pure stands of individual cereal varieties (Finckh et al 2000). Similarly, planting mixtures of willow varieties increases yields and reduces attack by rust disease (McCracken and Dawson, 1998).

Fast-growing short-rotation coppice crops also need less herbicides than many other crops because once they become established they out-compete weeds. Willow or poplar crops can be provided with nitrogen without the need for artificial fertilisers by intercropping with nitrogen-fixing plants such as clover or lupins (Granhall 1994).

Alder is especially interesting because it is one of the few woody crops in our northern climate that can fix its own nitrogen, which it does through symbiosis with the microorganism Frankia. Alder has been used in a “combined food and energy system” that integrates energy and food crops on the macro scale in an organic production system (Kuemmel et al. 1998).

There is a need to develop new intercropping systems designed especially to produce biomass for bioenergy. An example is the growing of winter legumes, followed by maize as a summer crop. This has many advantages with respect to yield and minimal use of nitrogen fertiliser

(Karpenstein-Machan and Stuelpnagel 2000). Both crops may be used in biogas plants, and the nutrients subsequently recycled to the farm.

Energy balance and global greenhouse gas balance

A prerequisite for an efficient and profitable energy crop is a positive energy balance. This means that when the biomass is converted to energy, this energy output has to be larger than the energy input needed to grow and harvest the crop, taking into account the energy costs of crop management, such as pesticides, chemical nutrients and machinery.

Energy balance is influenced by the cropping system. Table 8 shows energy balances for four energy crops – willow, *Miscanthus*, rye and oilseed rape – grown as monocrops by conventional farming in Denmark. All four show a large positive energy balance when the whole crop is used for energy.

For the crops in Table 8, the highest energy input is inorganic nitrogen fertiliser. Annual crops need about twice as much fertiliser as the perennial crops, so it is not surprising that the annuals rye and rape show lower energy balances than the perennials willow and *Miscanthus*. In the future it might be possible to use nitrogen-fixing alder in an organic cropping system (Jørgensen et al., 2003b). This would need only about half the input energy required by willow, so the ratio of energy output to input would rise to around 30.

One study made a detailed comparison of all energy aspects during the life cycles of two well-known bioen-

Table 8. Energy budgets for four crops delivered to the plant gate (GJ/ha/year). From Jørgensen & Kristensen (1996).

	Willow	Miscanthus	Winter rye	Winter rape
Yield (tonne dry matter/ha/y)	9	9	10	3 seed 2.6 straw
Dry matter %	50	85	85	91 seed 85 straw
Seeds, fertilisers, pesticides	5.3	4.9	11.2	11.5
Soil tillage, crop care	0.2	0.2	1.7	2.6
Harvest, storage and delivery	3.0	2.1	2.1	1.5
Indirect energy (machines, buildings etc.)	1.7	1.6	3.1	3.8
Fossil input total	10.3	8.8	18.1	19.4
Energy output (lower heating value)	147	161	171	116 (whole crop)
Output/input	14	18	10	6

6.1

ergy crops – short-rotation coppice willow and *Miscanthus* – and low-input mixed indigenous coppice wood with longer rotations. The conclusion was that if land area is the limiting factor, short-rotation coppice willow and *Miscanthus* give better results (Lettens et al 2003). However, this depends among other things on the fact that at present *Miscanthus* is almost free of pests and diseases. If *Miscanthus* is grown over large areas this situation could change, with negative consequences for its energy balance.

As well as providing energy, biomass is important for its ability to mitigate the greenhouse effect. Biomass provides energy without increasing the net amount of carbon dioxide in the atmosphere; if it replaces fossil fuel, then the amount of carbon dioxide falls. The performance of biomass in this respect is often measured simply by the amount of fossil fuel it replaces, but the truth is more complex.

In fact, different energy crops yielding similar amount of energy can show significantly different global greenhouse gas balances. This is because the global greenhouse gas balance takes into account carbon sequestration in the soil, as well as emissions of other greenhouse gases such as nitrous oxide and methane.

The large amount of straw used for energy in Denmark has recently been questioned because of its negative effect on soil carbon and soil quality (Christensen, 2002). Another study calculates that the annual crop triticale and the perennial *Miscanthus* may show differences of 30–70% in global greenhouse gas reduction when they replace identical amounts of fossil fuel (Olesen, 2002). The total emission reduction was calculated as 355–447 kt CO₂ equivalents/y for *Miscanthus* and 265 kt CO₂ equivalents/y for the same energy yield of triticale (Table 9).

These differences will become increasingly important when the Kyoto Protocol's Article 3.4 on land use effects comes into operation.

Further environmental perspectives

Biomass feedstocks are low-value bulk products. To make energy crops competitive with food and fodder crops, they need to provide other significant societal benefits. One example concerns water.

Water protection is a major environmental issue in Europe, and European agriculture struggles to meet the demands of the EU Directive on nitrates. Perennial energy crops have deep, permanent root systems, a long growing season and do not require the soil to be tilled for many years. These factors mean that after the first year, levels of nitrate in water percolating from the root zone are very low (Figure 8).

Total nitrate leaching from perennial energy crops on sandy soils in Denmark is estimated at 15–30 kg N/ha/y (Jørgensen & Mortensen, 2000) compared to about 75 kg N/ha/y as an average for conventional food and fodder crops. Water quality from perennial energy crops is further improved by the fact that these crops have very low pesticide requirements. In part this is because pests and diseases do not usually affect the quality of energy crops, and so do not need to be treated.

Recycling wastewater and other effluents by using them in agriculture is another worthy environmental technique that is often not used because of the risk of contaminating food products. This risk is reduced if the effluent is used on energy crops (Aronsson and Perttu, 2001), which are also very efficient at taking up nutrients mineralised from organic wastes. In Sweden more than 30 willow plantations are now used to recycle landfill leachate and domestic wastewater.

Some willow clones are quite efficient at taking up cadmium, and so may help to rid the soil of this unwanted metal. Cadmium enters the soil mainly in phosphate fertiliser (Eriksson et al., 1996), and can cause health problems even at low levels (Alfvén et al., 2000).

A fascinating feature of cadmium uptake by energy crops is that during combustion, careful control of the temper-

Table 9. Land area required in Denmark to produce 5 PJ-worth of biomass in triticale and in *Miscanthus* (harvested November or April). Figures for nitrous oxide emissions, energy consumption, fossil fuel substitution and carbon sequestration are compared with those for conventional cereal production using standard IPCC methodology (Olesen, 2002).

	Triticale	Miscanthus November	Miscanthus April
Area required for production of 5PJ (ha)	32140	24812	32797
Nitrous oxide emission reduction (kt CO ₂ equivalents/y)	20	30	36
Soil carbon sequestration (kt CO ₂ equivalents/y)	–45	37	108
Reduced energy use (kt CO ₂ equivalents/y)	5	3	18
Substitution of fossil fuel (kt CO ₂ equivalents/y)	285	285	285
Total emission reduction (kt CO ₂ equivalents/y)	265	355	447

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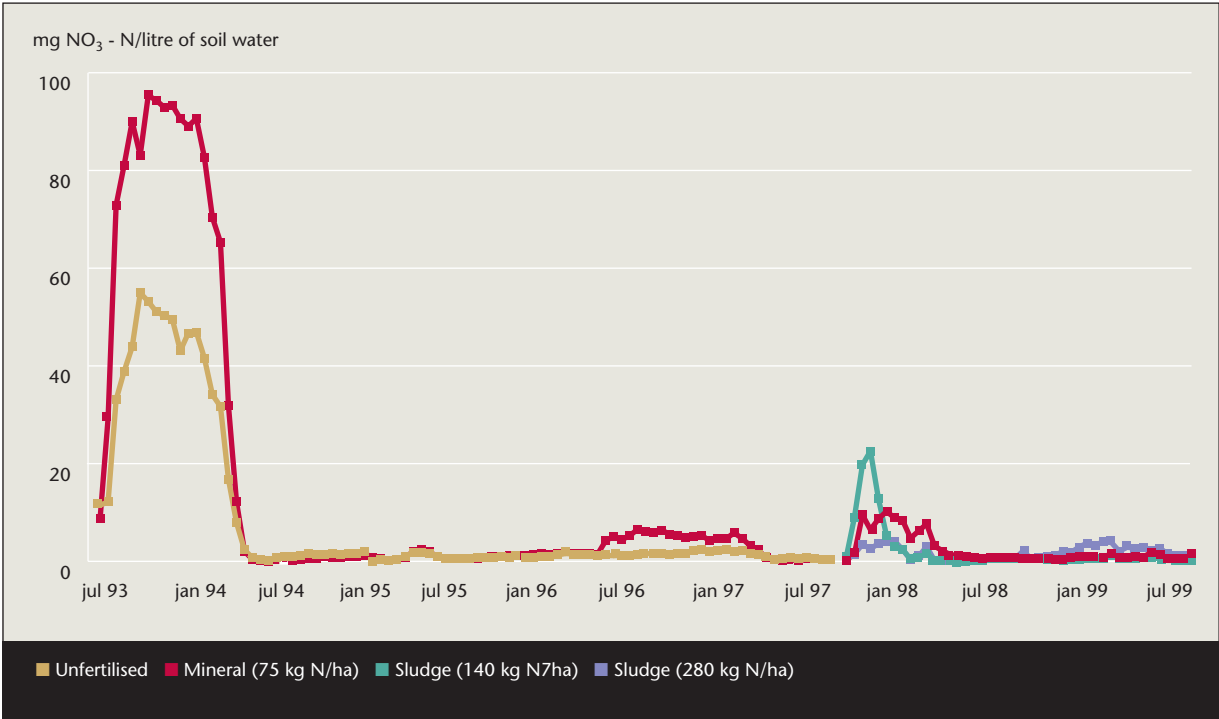
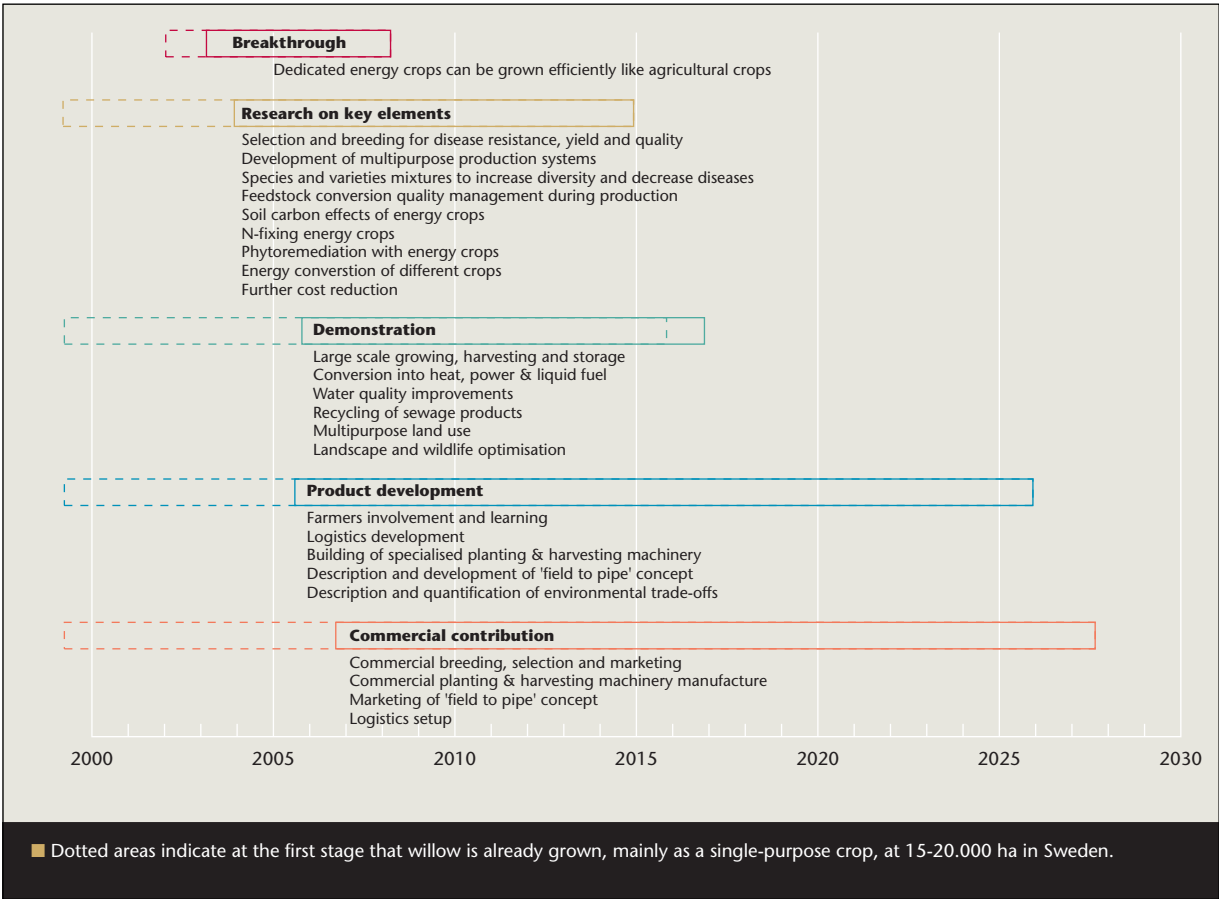


Figure 8. Nitrate measured as nitrogen in coarse sand below the root zone of willow at Jyndevad Research Station in Denmark. The treatments were: unfertilised, mineral fertiliser applied annually and municipal sludge applied in 1997 at two levels (Jørgensen & Mortensen, 2000).

Figure 9. Time scale from breakthrough to commercial contribution



6.1

atures in boilers and cyclones can concentrate the cadmium in a small fraction of the ash (Dahl & Obernberger, 1998). In this way cadmium may be extracted for re-use or disposed of in a small volume of ash.

These studies indicate that growing perennial energy crops may be a real win-win solution, delivering not only renewable energy but also clean water, better recycling and carbon sequestration in soils. However, some of these effects need further documentation and development. There is, for instance, still only very limited information on the long-term effects of energy crops on soil carbon levels (Mann and Tolbert, 2000) and on nitrous oxide emissions.

Conclusion

Using energy crops to produce electricity is an effective way to mitigate the greenhouse effect, mainly through the replacement of fossil fuels. Energy crops are a sustainable energy source, and they increase energy security by reducing the demand for coal and oil, most of which comes from outside Europe. They also have other environmental advantages, such as reducing nitrate pollution and absorbing heavy metals.

The available resources of surplus biomass will soon be

used up, but the growth in demand for renewable energy will almost certainly not stop there. The future is likely to see much greater use of perennial energy crops, which have many environmental and other advantages as part of a renewable energy system.

However, dedicated energy crops are quite different from conventional agricultural crops, and they are low in value. Farmers are unlikely to grow them unless a clear policy provides them with some degree of economic security.

Both farmers and the energy industry need clear signals from governments on the future of bioenergy, so that they can plan long-term investments in crops, machinery and power stations.

The whole energy crop chain should also be analysed for administrative and legislative bottlenecks that may hamper commercial development.

Finally there is a need for further breeding of specific energy crops with higher energy contents, lower energy inputs and optimised quality for downstream processing; for new intercropping systems with high resistance to pests and diseases; and for further R&D on cost reduction and environmental optimisation of the complete production chain.

6.2 Production and use of biodiesel

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Biodiesel is produced from vegetable oils that have been chemically modified by esterification; an example is rapeseed oil methyl ester (RME), made by treating rapeseed (canola) oil with methanol. Biodiesel can be burned directly in diesel engines. Robert Diesel himself was the first person to use vegetable oil as fuel for an internal combustion engine, in 1912, but it was not until the oil crisis of the 1970s that biofuels attracted serious interest. Biodiesel is reported to release fewer solid particles than conventional diesel, and because it contains no sulphur, it does not create the SO_2 which contributes to acid rain. Potentially even more important is the low level of carbon dioxide generation associated with biodiesel, at a time when CO_2 emissions are falling in every industrial sector except transport. Life-cycle studies show that 1 kg of biodiesel can reduce greenhouse gas emissions by at least 3.2 kg CO_2 equivalent.

Modern biodiesel development started in Austria around 1982, with four aims:

- to provide a secure supply of liquid transport fuels;
- to create an environment-friendly fuel for diesel engines;
- to reduce health and safety risks; and
- to provide customers with a reliable fuel at a reasonable ratio of costs to benefits.

The first biodiesel to become commercially available was RME, in 1988. At this time the product was of questionable quality, but tremendous progress has been made

since then. Developments include:

- broadening the feedstock beyond rapeseed oil;
- improving process technology through flexibility in processing multi-feedstocks (MFS) at high yields;
- developing sophisticated standards for assuring fuel quality;
- establishing biodiesel production in many countries all over the world;
- intelligent product positioning in defined fuel market segments;
- obtaining biodiesel warranties from diesel engine manufacturers and;
- implementing supportive legal measures and voluntary regulations.

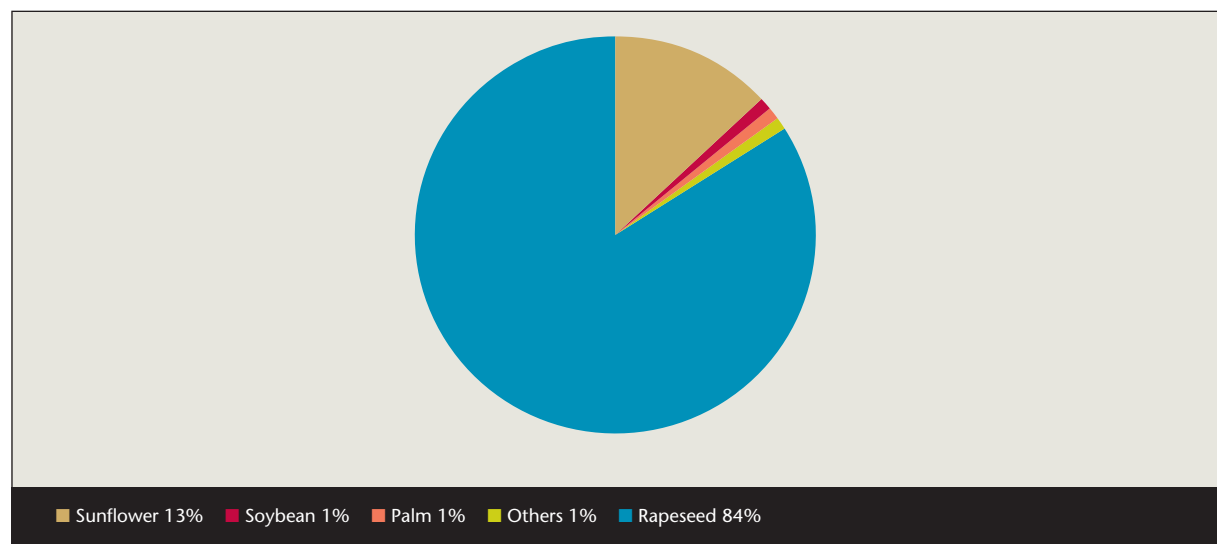
Feedstock

Oil from the rapeseed variety known as “00” was the first type of vegetable oil used for transesterification to produce biodiesel. Somewhat by chance, this oil is highly suitable, and it is still the main source of quality biodiesel (Figure 10).

Biodiesel from “00” rapeseed oil shows good stability and winter performance because the oil contains around 60% mono-unsaturated oleic fatty acids and only around 6% saturated fatty acids. New varieties such as LZ 7632 contain up to 87% mono-unsaturated oleic fatty acids. Using “precision farming” techniques, yields of rapeseed oil have been demonstrated at up to 2.9 t/h in northern Germany.

Over time, many other oils have been used successfully

Figure 10. Raw materials for biodiesel.



6.2

as biodiesel feedstocks (Figure 10). They include sunflower oil in southern France and Italy; soybean oil in the USA; and palm oil which fuels the buses of Kuala Lumpur, Malaysia. Recycled cooking oil can also be used; this technology was commercialised in 1998–9 during a time of high oilseed cost and record-low diesel prices.

Process technology

Soon after RME became established in the market, the search began for other feedstocks. A detailed screening of many types of oil and fat – virgin or waste, vegetable or animal origin – revealed that some feedstocks are unacceptable because they yield biodiesel with poor stability, winter performance, coking characteristics and so on. On the positive side, screening showed that good biodiesel can be made from a wide range of feedstocks and multi-feedstock (MFS) blends.

The key to producing low-cost biodiesel is to select clever blends of the cheapest feedstocks available, while maintaining acceptable product quality. Since the price and availability of different feedstocks can vary by the season or even by the day, it is a tremendous commercial advantage if production recipes can be changed quickly. In a modern biodiesel plant the cheapest blend of the day is selected from a range of recipes stored in the process control system.

After feedstock prices, yield is the second largest factor affecting profitability; a 10% drop in yield reduces profitability by approximately 25%. Early biodiesel plants had a transesterification yield of 85–95%, with the remaining 5–15% of the feedstock converted to less-profitable glycerine. Modern plants convert all the free fatty acids (FFAs) as well as the triglycerides, and so achieve yields of 100%.

Fuel standards and quality assurance

In the early days of biodiesel it became obvious that winning the confidence of diesel engine manufacturers would be of key importance. A working group was set up within the Austrian Standardisation Institute and the

first biodiesel fuel standard was issued in 1991 as ON C 1190 for RME. All the main tractor manufacturers went on to provide engine warranties based on this standard. ON C 1190 was followed in July 1997 by ON C 1191 for FAME (fatty acid methyl ester). This sophisticated standard was the first to define the quality of a fuel by what goes into the tank, not what it is made from. Later in 1997 Germany published the DIN E 51606 standard, which covers both RME and FAME, and other national standards were established in the CSSR, France, Italy, Sweden and the USA. The most recent development is a CEN draft standard for biodiesel with validity all over Europe. The final CEN standard, EN 14214, is currently due to be published in mid-2003.

All these standards are the basis for building customer confidence, obtaining biodiesel warranties from manufacturers of engines and injectors, ensuring reliability and creating a positive image for biodiesel.

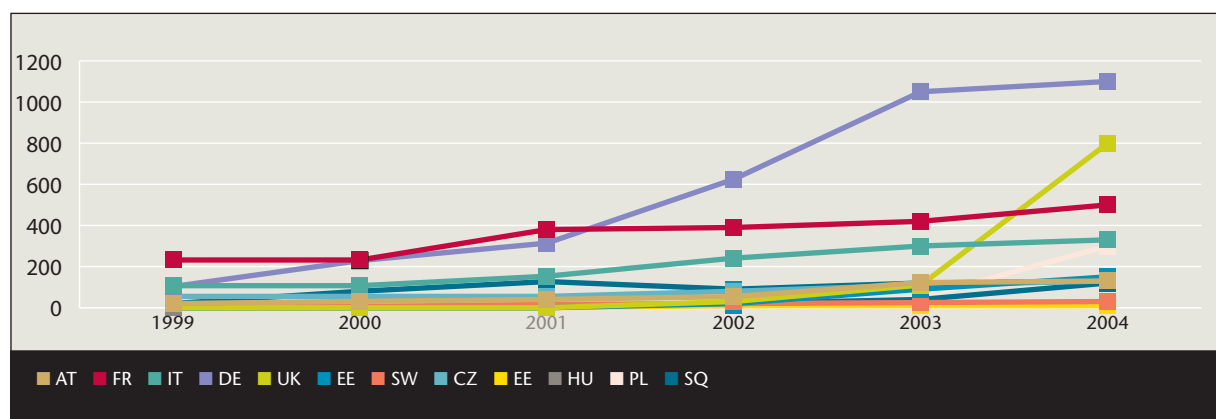
Production

Biodiesel production began in Austria in 1988 with a 500 t/y plant owned by a farmers' co-operative. Other plants soon followed, and the first industrial-scale biodiesel plant, with a capacity of 10,000 t/y, started up in Austria in 1991.

In the following years larger plants were established all over Europe. Examples are Livorno, Italy (up to 80,000 t/y), Rouen, France (at 120,000 t/y, the world's largest plant to date), Germany and Sweden. With 16 biodiesel plants, the Czech Republic is the leader in number of sites. The largest producer is Germany, which had capacity for 90,000 t/y in 1999 and plans 1,000,000 t/y by 2003, much of this in the former GDR (Figure 11).

The study *Review on Commercial Biodiesel Production World-wide* was commissioned by the International Energy Agency, carried out by the Austrian Biofuels Institute and published in April 1998. It identified 21 countries around the world where commercial biodiesel projects had been implemented. Europe remains the leader in biodiesel by

Figure 11. Biodiesel production in the EU-25. Copyright: Austrian Biofuels Institute 2003.



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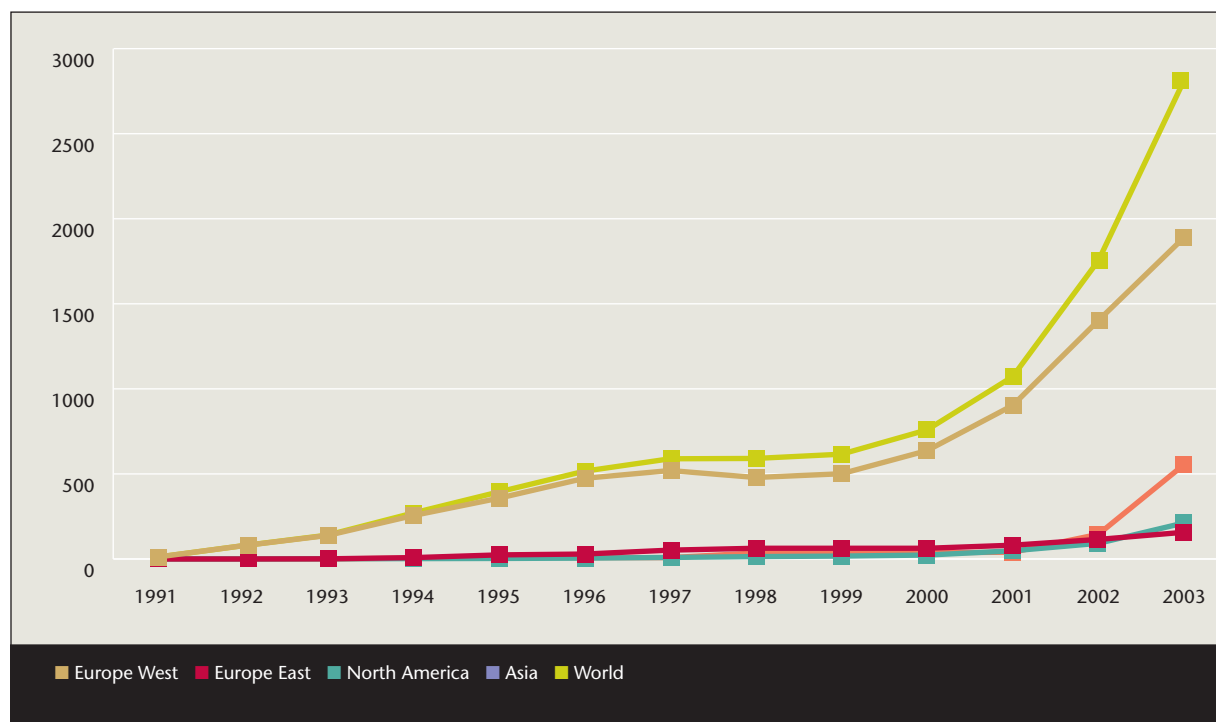


Figure 12. World biodiesel production. Copyright: Austrian Biofuels Institute.

a long way. US production has only very recently begun to increase, but the country is home to the very modern MFS plant operated by Griffin Industries in Kentucky (Figure 12).

Marketing

The present diesel market is completely dominated by fossil fuel. Biodiesel is an environment-friendly fuel with clear and substantial advantages over conventional diesel, but even at full production it could only ever meet around 8% of the diesel market. It is therefore up to professional marketers to identify market niches where the distinctive benefits of biodiesel will be best appreciated. Indicators of niche markets for biodiesel include environment-conscious customers who are prepared to pay more for a “green” product, and strict regulations on exhaust emissions, toxicity and biodegradability. Alternatively, biodiesel can simply be blended with fossil diesel, as in France. This approach retains many of the overall advantages of biodiesel, without requiring customers to be aware of what they are buying. With regard to upcoming environmental regulations e. g. EURO 4 (2005) and EURO 5 (2008), the future use of pure biodiesel in cars is uncertain. The improvement of the biodiesel quality as the new quality rule EN 14214 demands, is a right measure for the compatibility of biodiesel.

Diesel engine warranties

Historically, biodiesel was seen as a fuel for tractors and other agricultural machinery. As a result, the first engine

warranties covering the use of biodiesel were given by manufacturers of tractors and combine harvesters, including Same, Steyr, John Deere, Massey Ferguson, Lindner and Mercedes-Benz.

With the development of more sophisticated marketing strategies, warranties were extended to other diesel vehicles such as buses, taxis, boats and private cars. The most recent warranties cover the use of biodiesel in common-rail and other high-pressure fuel injection systems such as those supplied by Mercedes-Benz, Peugeot and Volkswagen.

Legal framework and regulations

The legal framework and regulations covering biodiesel have seen step-by-step progress that has taken very different paths in different countries. Among the observed motives for encouraging biodiesel are:

- increasing the security of energy supply;
- reducing dependence on fossil fuels;
- reducing greenhouse gas emissions;
- reducing local air pollution;
- protecting the soil and groundwater through the use of biodegradable products; and
- reducing health hazards by using non-toxic products.

The professional literature on biodiesel has grown impressively over the last 14 years. Publications now cover the spectrum from feedstock suitability to the performance of modern diesel engines, and from environmental advantages to experience in public bus fleets. The list of references includes some key publications.

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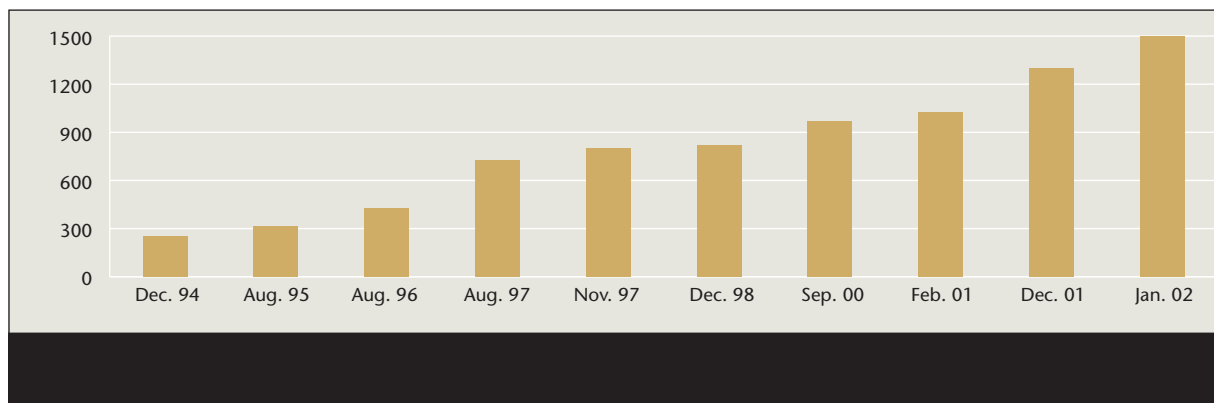


Figure 13. Development of the biodiesel filling station network in Germany, 1994–2002. Copyright: Austrian Biofuels Institute 2003.

Potential for biodiesel in the transport sector

The European Commission's Directive for the Promotion of Biofuels aims to raise biodiesel's market share to 2% by 2005 and 5.75% by 2010. These goals are widely seen as realistic and feasible; in Germany, biodiesel already has a 3% share of the diesel market and an increasing density of biodiesel filling stations (Figure 13).

The only limit to the production and use of biodiesel is generally the availability of feedstock. This does not have to be grown locally, but can be imported. Examples are North American soya oil, Malaysian palm oil, French sunflower oil, Greek cottonseed oil, Polish rapeseed oil and Danish cooking oil – recycled from McDonalds and other restaurants, and used for many years to produce biodiesel in Austria.

Denmark is well-suited to biodiesel for several reasons. The country's highly-qualified farmers and ideal climate produce high yields of rapeseed oil. A well-developed environmental consciousness will encourage Danish citizens to buy biodiesel and will allow effective cooking oil recycling schemes to be set up quickly.

Diesel engine technology for biodiesel

Recent years have seen impressive improvements in diesel engine technology to improve energy efficiency and reduce emission levels, driven by the EU Directive on Fuel Quality and the voluntary agreements defined in the Auto Oil programmes.

Modern diesel engines achieve their excellent performance through the use of high-pressure precision fuel injection equipment such as common rail systems. This requires fuels of correspondingly high quality, regardless of their origin.

European fuel standard EN 14214, which was developed in close co-operation with the automotive, oil and biodiesel industries, ensures that biodiesel is suitable for even the most modern engines. The standard forms the basis for warranties from leading car manufacturers, including Audi, BMW, Daimler-Chrysler, MAN, Seat, Skoda, Volvo and Volkswagen.

The latest technical development from vehicle manufacturers is a fuel sensor that measures the ratio of biodiesel to fossil diesel in the tank. By continuously optimising the injection timing to suit the fuel mix, it reduces emissions. The future of pure biodiesel use is not clear and must be specified by the car producer industry.

Driving forces and practical limits to the growth of biodiesel

The key driving forces for biodiesel in the EU today are the Directive for the Promotion of Biofuels and the Directive on Fuel Quality. The former is motivated by the need to cut greenhouse gas emissions in the transport sector and increase energy security by reducing dependence on imported oil. Also encouraging the growth of biodiesel are useful properties such as less local air pollution, rapid biodegradability, low toxicity to people and the environment, and high flashpoint.

The supply of biodiesel is limited, however, by the availability of oilseed crops. A biodiesel plan for Denmark should begin with a careful study of existing experience, followed by a survey of feedstock options – including recycled cooking oil. The next step is to identify those market segments in which the particular advantages of biodiesel can be put to best use. This will help to maximise the benefit to Danish citizens of a limited resource.

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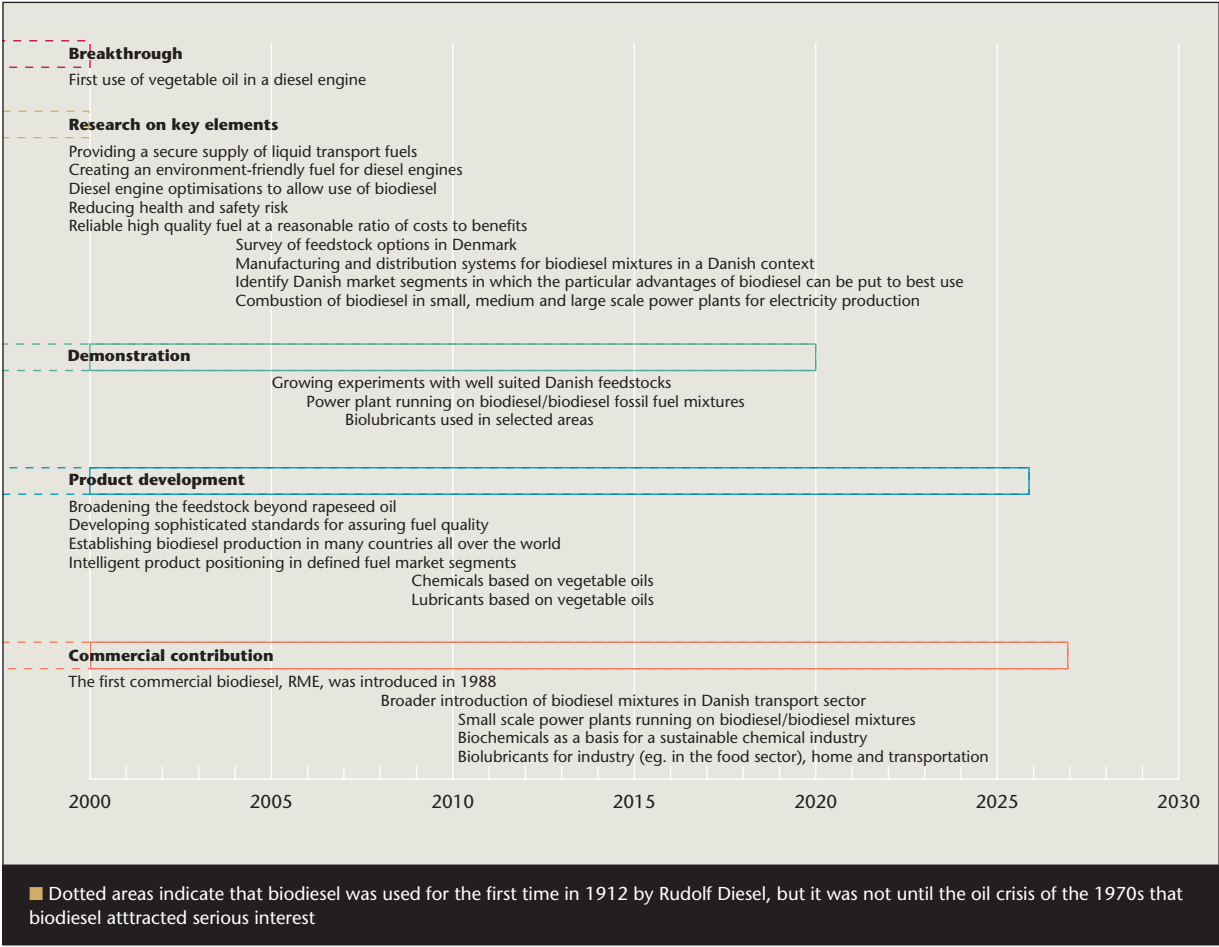


Figure 14. Time scale from breakthrough to commercial contribution

6.3 Combustion and gasification technologies

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Bioenergy conversion

There is a wide range of technologies to derive energy from biomass but, ultimately, the energy originates from combustion. Be it either the direct generation of heat or some complex process with intermediate conversion steps yielding motive power or electric energy.

The burning of wood and other solid biomass is the oldest energy technology used by man. Depending on the energy service demanded, it may be a very poor or a very good technology. A simple open-fire cooking stove has an efficiency of 10 to 15%, whereas a modern wood fired boiler utilises 85% of the energy for room heating.

Higher value energy services like motive power and electricity are derived from applying a thermodynamic cycle in a combustion engine or a turbine. We can distinguish between a direct and an indirect process, i.e. either the combustion gases serve as the working fluid in the thermodynamic process or the combustion heat is transferred to a secondary working fluid. In the direct cycle the combustion gases pass through the engine or the turbine. Modern energy conversion machines are designed and optimised for clean gaseous and liquid fuels. They are not well suited to burn biofuels and come in direct contact with the combustion products. Either the machines are adapted to burn solid biomass – which normally is not feasible – or the biomass is upgraded to a suitable liquid or gaseous fuel. Gasification is a basic step in the upgrading process – also to produce liquid fuels. The best known indirect cycle is the steam turbine with a separate combustor and boiler. A steam power plant, however, needs to be in MW-range to be efficient and economic. In the small kW-range the Stirling engine may become a technical option.

We may identify two basic preconditions for energy production from biomass:

Firstly, biomass, mostly in solid form, is not compatible with modern energy conversion technologies like combustion engines, gas turbines etc. Therefore, biomass must be converted to a liquid or gaseous fuel or used in an indirect cycle like a steam power plant.

Secondly, biomass is a local resource and, consequently,

the energy unit size is limited by the material available within a certain transport distance. Furthermore, biomass is not a standardised material and the utilisation technology will have to be adapted to the specific quality of the fuel.

The choice of conversion technology should be made in the light of the energy service demanded, i.e. heat, electricity or fuel. In Northern Europe the demand for heat is the largest end use sector, followed by transportation fuel and electricity. The overall conversion efficiency from field to final consumer is an important criteria for environmental compatibility and economics. For the future use of biomass it could serve as an indicator for the technology with the highest contribution to a sustainable energy system.

Combustion

Biomass may be used as a fuel in modern power stations and in some industrial processes to provide electrical power and heat, and in domestic stoves for cooking and heating purposes. By far most of the biomass currently used in the energy supply is converted by a combustion process, either in boilers or, mainly in developing countries, in domestic stoves. The most immediate use in Northern Europe is wood chips and pellets in domestic boilers in the residential sector. Modern boilers operate automatically and are in many regions an economic alternative, e.g. Austria and Finland.

Combustion technologies

Traditionally biomass in the form of wood, straw, and domestic, agricultural, and industrial wastes has been converted in grate or stoker type boilers. In large units a steam cycle is used to generate heat, electricity and process steam. During the last twenty years combustion technologies like suspension firing and fluidized bed have also been applied. Compared to grate fired boilers, the suspension firing technology offers higher electric power generation efficiency, lower operating costs and better load adaptation. The fluidized bed technology offers the potential for high fuel flexibility and build-in

Table 10. Global primary energy sources by 2000 (IEA "World Energy Outlook", 2002)

Modern biomass (biomass applied in boilers)	14.900 PJ
Traditional biomass (biomass applied in stoves for cooking and heating)	30.500 PJ
Other renewable (Hydro, wind)	2.800 PJ
Conventional sources (Oil, gas, coal, nuclear)	377.500 PJ

6.3

reduction of harmful pollutants. Grate and stoker type boilers are still used today when very problematic fuels are applied, when the boiler units are small, or when limited process and operation knowledge are available. More recent conversion technologies such as gasification or pressurized combined cycle combustion have been under development for many years. However, with respect to electric power generation efficiency and operating costs they are still typically less efficient than suspension firing boilers.

Use of biomass in simple stoves in the third world accounts for a very large fraction of the global consumption of energy (see Table 10). An increased application of modern biomass boilers in developing countries will provide both improved energy efficiency and a large reduction of harmful emissions.

Biomass applied for heat and electricity production should be converted in processes with a high efficiency and low operating costs. Furthermore the processes should be environmentally sustainable and they should provide a net reduction in CO₂ emissions. R&D can support those objectives by supporting the following type of activities:

- Increase the use of biomass by increasing the knowledge of combustion characteristics of different types of biomass.
- Improve efficiency and decrease operating costs for all types of biomass combustion units.
- Develop tools to minimize operational problems (i.e., with fuel handling, corrosion and ash deposits).
- Develop methods to remove harmful emissions and to make appropriate utilization of residual products.
- Develop methods such that biomass can be applied for power generation on high efficiency suspension fired and fluidized bed boilers.

Pretreatment of biomass

Fuel pretreatment involves the steps necessary to upgrade a harvested biomass resource to a usable fuel. It is aimed at partly at reducing storage, transport and handling costs and partly at providing a homogeneous fuel that is suitable for automatic fuel-feeding in combustion systems. The pretreatment process depends on the type of biomass as well as on the preferred combustion technology. It may involve baling (herbaceous biofuels), particle size reduction, and, if necessary, drying. Various pretreatment techniques are discussed in detail elsewhere [1].

Operational problems in biomass combustion

Biomass has a number of characteristics that makes it more difficult to handle and combust than fossil fuels. The low energy density is the main problem in handling and transport of the biomass, while the difficulties in using biomass as fuel relates to its content of inorganic constituents. The herbaceous types of biomass com-

monly used in Denmark contain significant amounts of chlorine, sulfur and potassium. The salts, KCl and K₂SO₄, are quite volatile, and the release of these components may lead to heavy deposition on heat transfer surfaces, resulting in reduced heat transfer and enhanced corrosion rates. Severe deposits may interfere with operation and cause unscheduled shut downs. The release of alkali metals, chlorine and sulfur to the gas-phase may also lead to generation of significant amounts of sub-micron particles (aerosols) along with relatively high emissions of HCl and SO₂.

The nature and severity of the operational problems related to biomass depend on the choice of combustion technique. In grate-fired units deposition and corrosion problems are the major concern. In fluidized bed combustion the alkali metals in the biomass may facilitate agglomeration of the bed material, causing serious problems for using this technology for herbaceous based bio-fuels. Fluidized bed combustors are in frequent use for biomass, e.g. wood and biogenic waste material, circulating FBC are the preferred choice in larger units. In the power range of 20 MW-el an efficiency of 30–35% is achieved with a modern steam cycle.

Application of biomass in existing boilers with suspension-firing is considered an attractive alternative to burning biomass in grate-fired boilers. However, also for this technology the considerable chlorine and potassium content in biomass, particularly in one-year crops such as straw, may cause problems due to deposit formation, corrosion, and deactivation of catalysts for NO removal (SCR). Currently wood based bio-fuels are the only biomasses that can be co-fired with natural gas; the problems of deposition and corrosion prevent the use of herbaceous biomasses. However, significant efforts are aimed at co-firing of herbaceous biomass together with coal on existing pulverized coal burners. Co-firing with coal has been successfully demonstrated and the most modern unit built in Denmark, Avedøre 2. For some problematic fuels, esp. straw a separate auxiliary boiler may be required. In addition to the concerns about deposit formation, corrosion, and SCR catalyst deactivation, the addition of biomass in these units may impede the utilization of fly ash for cement production. In order to minimize these problems, various fuel pretreatment processes have been considered, including washing the straw with hot water or using a combination of pyrolysis and char treatment (washing or gasification or low-temperature combustion). However, during the combustion process the coal ash may capture a significant fraction of the alkali metals released from the biomass and thereby lower the problem with deposition/corrosion and SCR deactivation. Furthermore, fly ash with a certain fraction of biomass ash has now been accepted for cement production. For these reasons, pre-treatment of the straw can be avoided by choosing specific coals and keeping the straw share of the fuel mixture below a critical value. A preliminary conclusion would be that the steam cycle

6.3

is the only commercial technology for power generation from biomass today. The units need to be in the region above 5 to 10 MW to achieve an acceptable efficiency of 25 to 30%. Higher efficiencies are achieved with co-firing, taking advantage of the good steam parameters, frequently super critical, in large power station of the 100 MW class and more.

Gasification

The gasification of wood fuel has a long tradition, especially in small units. The technology can also draw on experience gained with lignite and hard coal. Over the years a large number of gasifiers have been built and partly developed to an industrial level. In particular, a considerable effort has been made towards the use of gasification as part of CHP strategies. Further, the technology has been automated to a level approaching other biomass based power generation systems.

One reason for considering gasification is that the combustion of solid biomass is changed into the much more attractive process of burning a gas and the inorganic material present in the biomass does not enter the final combustion zone.

Modern gasification technology with high quality standards for the product gas is a complex process.

The product gas consists mainly of H_2 , CO, CH_4 , and CO_2 and is mostly intended for immediate use on site and the gasification unit is an integral part of the power generating plant. In the small unit size the gas is mostly used in a combustion engine and in the larger units in a gas turbine or combine cycle plant. In this way a higher efficiency of the biomass conversion can be obtained. In consequence, the size of the gasifiers and the energy conversion technology must be optimised to integrate all energy flows such as waste heat from quenching and cooling the raw gas.

Technology platforms

The gasifiers fall into three categories:

- Fixed bed gasifiers.
- Fluidised bed gasifiers.
- Entrained flow gasifiers.

The fixed bed gasifiers are mostly small scale and come in two types, either down-draft (<2 MW) or up-draft (<10 MW). They differ in the direction of gas flow through the biomass in the reactor. In the up-draft gasifiers the raw gas contains important fractions of tar which need to be removed before using the gas. The down-draft reactor enables the cracking of the high hydrocarbon fraction but a drawback is the high gas temperature at the outlet. The fluidised bed gasifiers, either stationary, SFB, or circulating, CFB, are in the MW-range. The circulating variety, CFB, requires a size of more than 15 MW to be commercially viable. The product gas is characterized by low tar content and also sulphur and chloride may be absorbed in the bed material. Thus, fluidised bed gasifiers

apparently reduce significantly the problems associated with the utilization of agricultural biomass.

Entrained flow gasifiers operate at very high temperatures, 1200 to 2000°C and require biomass in form of very finely ground particles. Again there are a number of different types. A special feature is the utilisation of the high temperature heat in the raw gas which is quenched after leaving the reactor.

The cold gas efficiency, describing the heating value of the gas stream in relation to that of the biomass stream, is in the order of 55 to 85%, typically 70%. For biomass air is mostly used as the gasifying medium. Pure oxygen or steam is seldom used as the complexity of the process scheme is hardly justified. The heating value of the gas, mostly consisting of CO and H_2 , is in the region of 5 MJ/m³ or roughly one sixth of natural gas. In comparison, biogas from anaerobic fermentation with a high methane content has a heating value corresponding to one half of natural gas.

Gas quality and environmental issues

A major challenge has been to develop gas-cleaning strategies to meet the stringent requirements of gas quality. Two methods deserve to be mentioned, namely the wet gas cleaning procedure developed by Babcock & Wilcox Volund (BWV) and the high temperature two-stage gasification as developed at the Technical University of Denmark. The methods are part of the 6 MW_{TH} CHP demonstration plant (Harboøre, Denmark) and the 75 kW staged gasifier ("Wiking") at the Technical University of Denmark, respectively [2,3].

The BWB method is based on gas cooling and wet electrostatic precipitation. A prerequisite for fuelling engines with the product gas is that the gas temperature is lowered to approximately 40°C. This temperature drop causes the release of a large quantity of a water/tar condensate. The wastewater has been a significant problem due to its high content of light tar compounds. However, a novel process for cleaning the wastewater ensures a 99.98% cleaning efficiency and, hence, that the water can be discharged without restrictions. Furthermore, an even more compact cleaning system based on supercritical wet gasification/oxidation is currently being developed.

The main advantage of the two-stage gasification process is, that contrary to most other gasifiers, very small amounts of tar is present in the produced gas. This is the result of a highly efficient, on-line gas cleaning based on a high temperature, reactive bed. So the costs for gas cleaning before use of the produced gas in gas motors or turbines can be significantly reduced.

It is a characteristic feature that the developed procedures for gas cleaning demonstrates efficiencies well above 99.9%.

The emission from CHP gasification plants seems not to present specific problems with the exception of CO. The Danish regulations request in general CO-levels below

6.3

500 mg/Nm³ in the exhaust. This limit is the result of an apparent coupling of the CO emission with the emission of PAH in combustion processes. This is obviously not the case using a partly CO based fuel. On the other hand, a simple catalyst system may reduce the CO emission close to the present limits.

The ash seems to have a low carbon level and is tested negative for dioxin and PAH's and may, hence, be used as a fertiliser in agriculture/plantations.

Towards the green fuel cell

Electricity production by SOFC fuel cells is one road to obtain a high efficiency in electricity production. In order to meet this demand in a sustainable way, gasification and SOFC fuel cell conversion systems based on biomass, should obviously be considered. The most cost-effective size has been estimated to be plants up to 30 MW_E and electric efficiencies well above 50% are expected.

The highly purified gasification gas has the potential to be used directly in SOFC cells or alternatively steam-reformed. In this case, steam gasification of biomass would directly enhance the hydrogen content in the crude gas. The biomass-hydrogen route could be a promising future technology bringing a green fuel cell to reality.

Liquefaction of biomass

Thermal conversion of biomass has been investigated for many years as a possible source of renewable liquid fuels. Fast pyrolysis is an advanced process which gives a yield of bio-fuels up to 80% on dry feed, typically, 65% liquids and 10% non-condensable gases. The characteristic features of fast pyrolysis are the very high heating and heat transfer rates, a carefully controlled pyrolysis temperature and a rapid cooling of the products. The process may

advantageously be carried out on CFBs modified to operate at low temperatures. However, the technology is still at a relatively early stage.

The liquid bio-fuels are storable and have the advantage of separating the fuel production from the utilisation. They can substitute fuel oil in any stationary heating or power generating application and have a heating value of about 40% of a conventional fuel. Thus, bio-fuels may well find use at peak loads at large power plants. The dominant use of liquid bio fuels is in the transportation sector, at least on the continent. Oil from plants, especially rape seed is obtained in pressing and extraction and can be used directly in dedicated engines. In a subsequent process a methylated ester is produced with a quality comparable to diesel fuel. It is marketed as "Bio-diesel" or is blended with standard diesel.

A different approach is to convert the gas from the gasification of biomass in either a methanol synthesis process or a Fischer-Tropsch process yielding light hydrocarbons. Both products can be used as straight fuels or as blends. The efficiency of the total processing route is a critical parameter. The costs are obviously higher than similar products from mineral oil. The tax regime and the national fiscal policy are determining factors in market penetration.

Conclusion

- The combustion of solid biomass to produce heat is an established and (mostly) economic technology in the whole power range. Especially for small units in the residential sector a further market penetration would require a convenient and user friendly fuel supply and service infrastructure.
- The combustion of biomass to electricity is today technically and economically only feasible with the steam cycle in the larger MW-units, especially in co-firing.

Table 11. Qualitative comparison of technologies to produce electricity, heat and/or power from biomass. + relatively poor or low, +++ relatively good or high, # relatively cheap, ##### relatively expensive.

Technology	Economics	Environment	Market potential	Present deployment
Combustion - Heat	+++	#	+++	+++
Combustion - Electricity	++(+)	##	+++	++
Gasification	+(+)	###	+++	
Pyrolysis	(+)	#####	++(+)	

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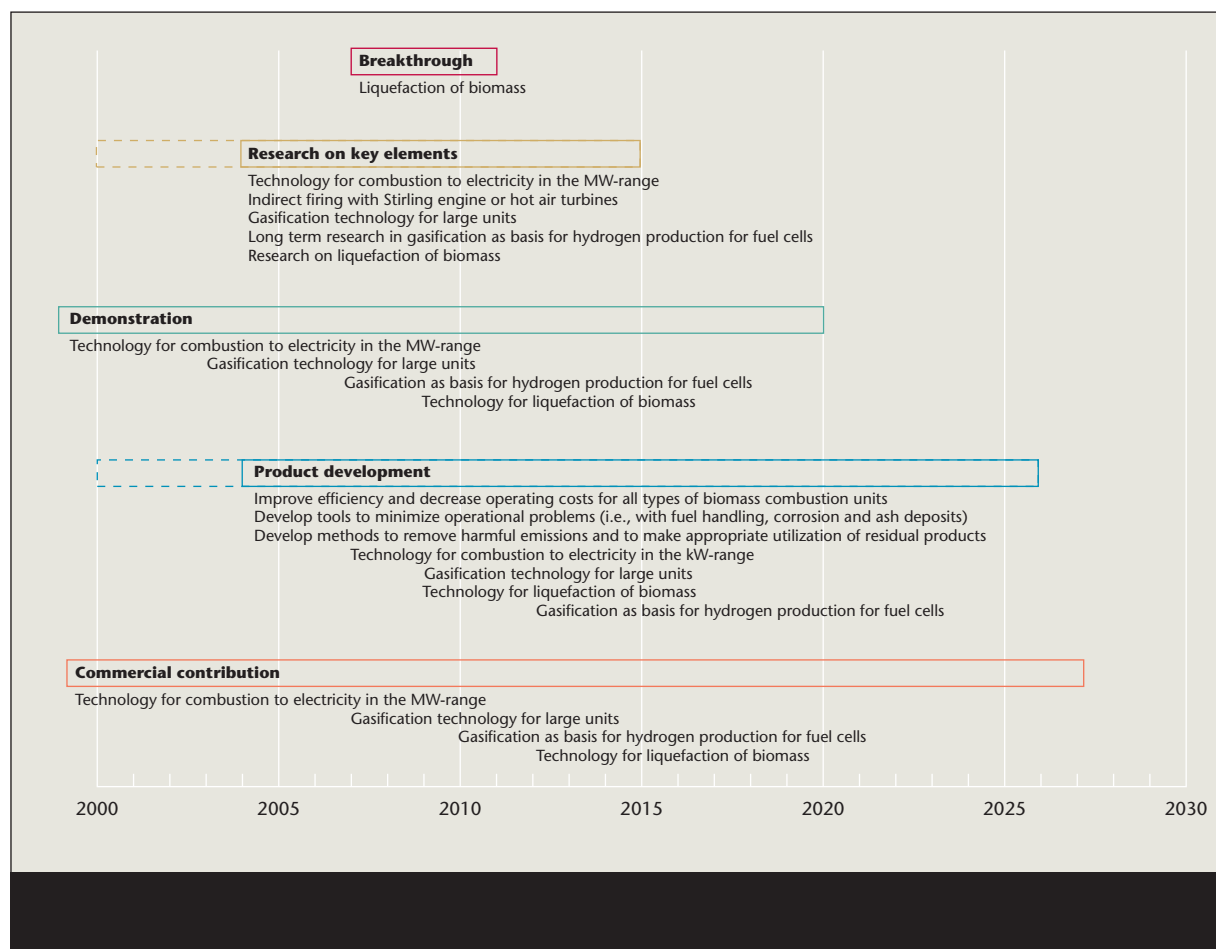


Figure 15. Time scale from breakthrough to commercial contribution

There is no technology available in the kW-range. On the longer time scale indirect firing with Stirling engine or hot air turbines appears promising.

- Thermochemical gasification allows to transform (almost) all biogenic feedstock into a low caloric gas which can be utilised in a broad range of technologies. The gasification technology is in the demonstration phase and still has technical and economic deficits, especially in small units. The potential applications are

large, primarily for electricity and heat. On the longer time scale, gasification could be the basis for hydrogen production for fuel cells.

- The upgrading of biogas to a liquid fuel would open a large range of potential applications. The process chain entails, however, a number of conversion losses and does at present not appear to be the most efficient use of the biomass resource potential.

6.4 Biotechnology in ethanol production

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Introduction

Ethanol has been made since ancient times by fermenting sugars. All the ethanol used for fuel and alcoholic drinks, and most industrial ethanol, is made by this process (Licht 2001). In 2002, world ethanol production was projected at 34 million m³ (Licht 2002).

Fuel ethanol is also known as bioethanol, since it is produced from plant materials by biological processes. Fuel ethanol is the largest market by far, accounting for 60% of total ethanol production worldwide (Licht 2001). This share is likely to increase over the coming years as many countries set up fuel ethanol programmes. Industrial ethanol accounts for 20% of the market and beverages for about 15%; both these markets are growing comparatively slowly.

The world's largest ethanol producers are Brazil and the USA, which together account for more than 65% of global ethanol production; the figure for Europe is 13%. Fuel ethanol is produced in Brazil mainly from sugar cane and in the USA from corn, accounting for 11.9 and 7.6 million m³ respectively in 2001 (Licht 2001). In the USA, ethanol has been used successfully in clean fuel programmes in Minnesota, Wisconsin, Oregon and the Chicago metropolitan area (Vaghn, 1999).

Because bioethanol is a renewable fuel it is commercially available transport fuel that helps to reduce emission of carbon dioxide (Vaghn 1999, Macedo 1998). Fossil fuels release carbon dioxide into the air when they are burned, but bioethanol is "CO₂-neutral" because the carbon dioxide released by burning is absorbed from the atmosphere by the next generation of crops used in the manufacture of bioethanol.

A recent report by Argonne National Laboratory concluded that, compared to gasoline, using ethanol from corn reduces the demand for fossil-fuel energy by 50–60% and cuts greenhouse gas production by 35–46%. For ethanol produced from cellulosic materials, these reductions are even greater (Vaghn, 1999).

Bioethanol as a fuel

Ethanol is a clear, colourless, flammable, oxygenated hydrocarbon with the chemical formula C₂H₅OH. Ethanol can be used as a transport fuel in at least four forms: anhydrous ethanol (100% ethanol), hydrous ethanol (95% ethanol and 5% water), anhydrous ethanol-gasoline blends (10–20% ethanol in gasoline) and as raw material for ethyl tert-butyl ether (ETBE) (Wyman and Hinman, 1990).

An anhydrous blend of 10% ethanol in gasoline (E10) is sold as "gasohol" in the USA and Canada. In Brazil, up to

90% of new cars have engines specially designed to run on hydrous ethanol. This avoids the expense of removing the remaining 5% of water, and also takes advantage of the fact that water increases the octane number and latent heat of evaporation of ethanol (Wyman and Hinman, 1990).

As a fuel, ethanol competes with gasoline (petrol), diesel and MTBE (methyl tert-butyl ether, added to gasoline at a concentration of 5–10% as an octane booster).

Compared to gasoline and diesel, ethanol is per litre more expensive and has a lower energy density, so more is needed to drive a given distance (Table 12). Compared to MTBE, however, ethanol is comparable regarding price per energy unit and has considerable environmental advantages.

Table 12. Heating values and prices (May 2003) of fossil fuels and ethanol.

Fuel	MJ/kg	MJ/l	Price* kr/l
Gasoline (regular 95)	42.7	31.4	2.15
Diesel	42.5	35.5	2.09
MTBE	35.2	26.7	3.10
Ethanol	27	21.4	2.47
*without taxes or transport			

MTBE is added to gasoline as an octane booster, replacing the lead formerly used for this purpose, and to reduce emissions of smog-forming air pollutants. Because MTBE is made from fossil fuels, however, it is a net contributor to greenhouse gas emissions. MTBE is also a serious pollutant in groundwater because it is water-soluble, highly toxic and resists biodegradation. Ethanol biodegrades quickly in soil and water and is not toxic in small amounts (quantities).

It therefore seems clear that the biggest advantages will come from replacing MTBE with ethanol. However, ethanol has several advantages compared with gasoline and diesel as well as MTBE:

- positive net energy balance;
- less severe impact on the environment (both air and groundwater);
- less dangerous to health;
- reducing dependence on oil imports;
- helps maintain rural economies; and
- promotes biotechnology.

6.4

Raw materials

Sugar is required to produce ethanol by fermentation. Plant materials (grain, stems and leaves) are composed mainly of sugars, so in principle almost any plants can serve as feedstock for ethanol manufacture.

In practice, the choice of raw material depends on what grows best under the prevailing conditions of climate, landscape and soil composition, as well as on the sugar content and ease of processing of the various plants available. The result is a wide variety of ethanol feedstocks, and hence production processes.

Most bioethanol is produced from sugar cane (Brazil), molasses and corn (USA), but other starchy materials such as barley, rye and wheat are also suitable. Bioethanol can also be produced from forest and agriculture residues such as wood chips and straw from corn, wheat, rye, oat, barley and rice. With a total sugar content of 60–70% (40% glucose as cellulose and 25% xylose as hemicellulose), wheat straw can produce around 230 kg of ethanol per tonne of dry material. Table 13 shows estimated ethanol yields from various feedstocks.

Ethanol production

The production of bioethanol requires two steps: fermentation and distillation. Practically all ethanol fermentation is still based on Baker's yeast (*Saccharomyces cerevisiae*), which requires simple (monomeric) sugars as the raw material. Conventional yeast fermentation produces 0.51 kg of ethanol from 1 kg of any the C₆ sugars glucose, mannose and sucrose (the last reaction in Figure 16).

Molasses is a by-product of the cane sugar and beet sugar industries. Compared with other feedstocks, molasses has the advantage that it contains around 50% of simple sugars that can be fermented directly to ethanol (Table 13) (Murtagh 1995).

However, not all feedstocks contain simple sugars. In grain, for example, glucose molecules are linked by α -1-4 bonds to create starch. Many plant materials contain lignocellulose, in which glucose molecules are linked by β -1-4-bonds. In both cases, hydrolysis (the addition of water, for instance by enzymes) is needed to break these bonds and produce simple C₆ sugars for fermentation (the first reaction in Figure 16).

Yeast and other microorganisms can also produce ethanol from simple C₅ sugars such as xylose, which is

Table 13. Raw materials, processing temperatures and enzymes for pre-hydrolysis, content of fermentable sugars and potential ethanol yields per 100 g dry weight.

Raw material	Temperature (°C) used for pretreatment/enzymatic hydrolysis	Enzymes (type)	Hexoses (g/100g)	Pentoses (g/100g)	Ethanol potential (g/100g)
Sucrose and starch					
Molasses	None	None	50	0	32
Sugar cane	None	None	65	0	28
Corn	130–160/52	Amylases	76	0	32
Wheat	130–160/52	Amylases	72	0	31
Rice	130–160/52	Amylases	80	0	34
Rye	130–160/52	Amylases	70	0	30
Barley	130–160/52	Amylases	72	0	31
Potato	130–160/52	Amylases	56	0	24
Lignocellulose					
Bagasse	190–210/50	Cellulases	45	25	26
Corn stover	190–210/50	Cellulases	41	25	25
Wheat straw	190–210/50	Cellulases	37	25	23
Aspen	190–210/50	Cellulases	51	17	26
Willow	190–210/50	Cellulases	40	12	19
Spruce	190–210/50	Cellulases	61	5	25
Waste					
Municipal solid waste	190–210/50	Cellulases	42	18	23
Cellulose sludge	190–210/50	Cellulases	39	7	17

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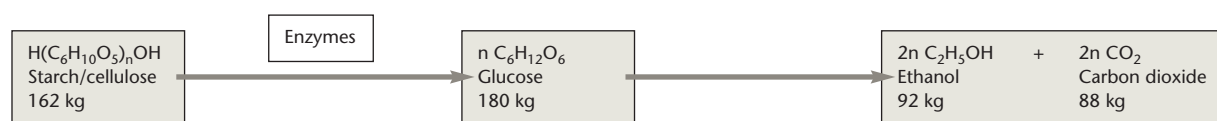


Figure 16. Hydrolysis of starch and cellulose followed by fermentation of glucose to ethanol using Bakers's yeast.

derived from hydrolysis of the polymer hemicellulose, itself a component of lignocellulose (McMillan, 1994b). The hydrolysis step that precedes fermentation requires a combination of physical and chemical conditions that is normally specific to the type of material being processed (Wyman, 1994). In particular, starchy and lignocellulosic raw materials need different enzymes and hydrolysis regimes, so they are considered separately in the following sections.

Fermentation of starch to ethanol

Wet milling and dry milling

For fermentation processes based on starch, the raw material is usually some kind of grain. To release the starch, the grains must first be broken open. The two most widely used methods of doing this are wet milling and dry milling (Licht 2001).

In wet milling the grain is first steeped in a solution of water and sulphur dioxide for 24–48 hours at a temperature of around 52°C, and then passed through mills to loosen the germ and the hull fibres. In dry milling the grain is broken up into particles that are as small as possible, to facilitate subsequent penetration of water.

Hydrolysis and fermentation

Once milled, the starchy material must be “saccharified” to convert the starch into fermentable sugars. This is normally done with the help of enzymes known as amylases, whose job is to hydrolyse starch.

In its natural state, starch exists as compact crystalline granules that are resistant to enzymatic attack. To help the enzymes work better, heat is used to dissolve the starch molecules.

The milled grain is first made into a slurry in water. A small quantity of α -amylase is added to reduce the viscosity, and the slurry is then cooked at 130–160°C. Once the starch has gelatinised, the resulting “mash” is cooled to 80–90°C and the rest of the α -amylase is added, producing rapid liquefaction.

When the mixture has cooled to 32°C, a mixture of amyloglycosidase and yeast is added. Amyloglycosidase is an enzyme that performs the main hydrolysis step, after which the yeast converts the resulting simple sugars into alcohol.

This process (Figure 16) of carrying out the enzymatic liberation of glucose and the fermentation in a single process step is known as SSF (simultaneous saccharification and fermentation).

Traditional fermentation, known as SHF (separate hydrolysis and fermentation), uses separate steps and dif-

ferent process conditions for the enzymatic pre-treatment and the fermentation. SSF gives higher yields because it minimises substrate (glucose) inhibition.

Fermentation of lignocellulose to ethanol

Lignocellulosic materials such as straw and wood, which are often available as wastes, are much cheaper than grain. Converting them to ethanol, however, requires complex and costly processes. For lignocellulosic materials to become economic as ethanol feedstocks requires the development of new technologies.

Lignocellulosic materials contain two types of polysaccharides, cellulose and hemicellulose, bound together by a third component, lignin. From the point of view of ethanol fermentation, they are hard to work with for two reasons. First, the lignin protects the cellulose and hemicellulose from attack by enzymes. Second, when enzymes do manage to reach the cellulose and hemicellulose they are hindered by the crystalline structure of these molecules.

Pre-treatment

The first step in processing lignocellulosic materials is a pre-treatment step in which some of the hemicellulose dissolves in water, either as monomeric sugars or as oligomers and polymers. The temperature range is normally 150–200°C. The main processes are:

- steam explosion;
- treatment with ethanol/water mixtures (the Organosolv process); or
- high-temperature/high-pressure treatment with acid alkalis, oxygen or both.

This is followed by treatment with enzymes known as cellulases and hemicellulases, which hydrolyse cellulose and hemicellulose respectively. The effectiveness of the enzymes depends on their origin (Thygesen et al. 2003), the nature of the previous treatment step(s) and the properties of the feedstock, notably the degree of cellulose crystallinity and the amount and type of lignin. Pre-treatment using alkali and oxygen (wet oxidation) effectively removes lignin without producing toxic compounds and seems to give the best performance at the enzyme treatment stage when treating annual crops like wheat straw (Bjerre et al., 1996; Klinker et al., 2002, 2003).

Hydrolysis and fermentation

Following pre-treatment, the next step is to use enzymes to hydrolyse the cellulose fraction and release glucose. This step takes place at 50°C, with the enzymes added as

6.4

Xylose → 30% Ethanol + 8% Acetate + 2% Lactate + 40% CO + 20% Hydrogen

Figure 17. Conversion of xylose to ethanol by the thermophilic bacterium *Thermoanaerobacter mathranii*.

a mixture of cellulase and β -glucosidase. The actual fermentation is a two-stage process. In the first stage, glucose is fermented at 32°C with traditional Baker's yeast (Figure 16). As in starch fermentation, enzymatic hydrolysis and fermentation can be carried out simultaneously (the SSF process).

The second fermentation step converts pentoses – mainly xylose – into ethanol. This is done using special genetically-modified microorganisms or selected natural strains (Zaldivar et al., 2001) (McMillan, 1994a). The anaerobic bacterium *Thermoanaerobacter mathranii* (figure 17), discovered in a hot spring in Iceland, can convert xylose to ethanol at 70°C (Larsen et al., 1997). A genetically-modified *Escherichia coli* has also been developed to convert all the sugars present in lignocellulosic hydrolysates to ethanol (Beall et al. 1991).

Co-production of bioethanol and biogas

Since 1994 the Technical University of Denmark and Risø National Laboratory have been co-operating on a new technology for producing both bioethanol and biogas (Figure 18) (Ahling and Thomsen, 2000). Such a process would eliminate the disadvantages of conventional, separate, bioethanol and biogas plants.

Conventional biogas plants use only 50% of their feedstock. The remainder consists mainly of lignocellulosic

materials, which make up a large proportion of animal manure. These pass almost unconverted through the biogas plant.

Bioethanol plants, on the other hand, are designed to work with starch or celluloses. Lignins and other components which cannot be turned into fermentable saccharides are treated as effluent, which itself requires a further cleanup process, or at best burned as low-quality boiler fuel.

Co-production of bioethanol and biogas would allow all the components of both plant biomass and animal manure to be used. The wastewater from the ethanol plant, containing lignin and its oxidation products, as well as by-products of fermentation, acts as a secondary feedstock for the biogas reactor, resulting in a reduced cost price for ethanol of approximately 35% due to biogas production.

Perspectives

In summary, bioethanol is a renewable fuel that can reduce dependence on foreign energy, stimulate the rural economy, cut emissions of greenhouse gases and reduce contamination of waterways and groundwater following accidental spills.

In USA, the market on bioethanol is driven by the political out-phasing of MTBE. In Europe, a new directive

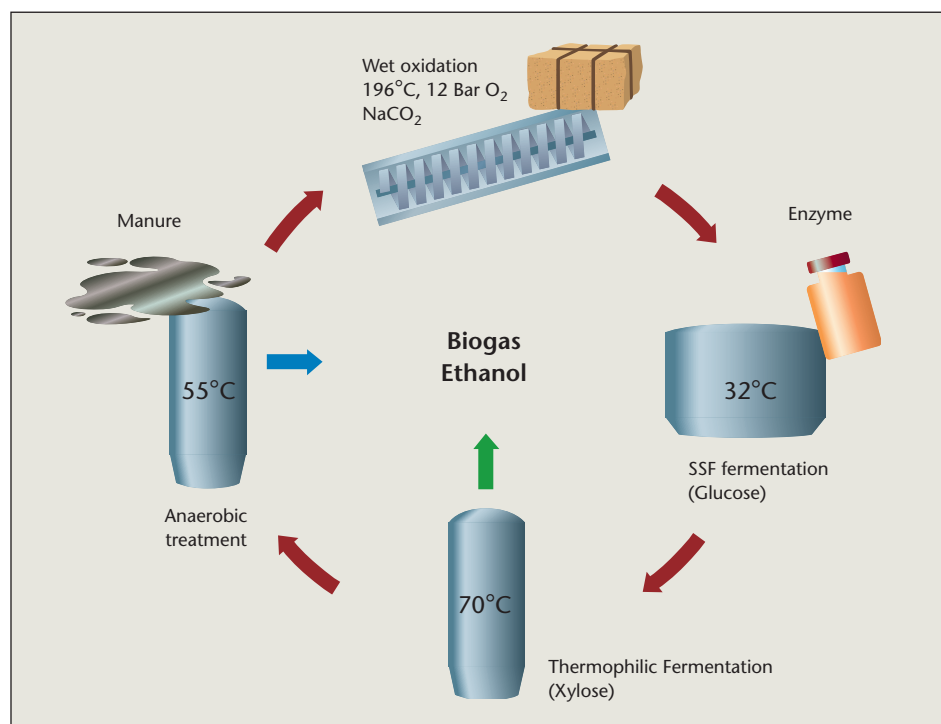


Figure 18. Danish Bioethanol Concept: straw and manure are used to produce bioethanol and biogas in an integrated plant that recycles process water.

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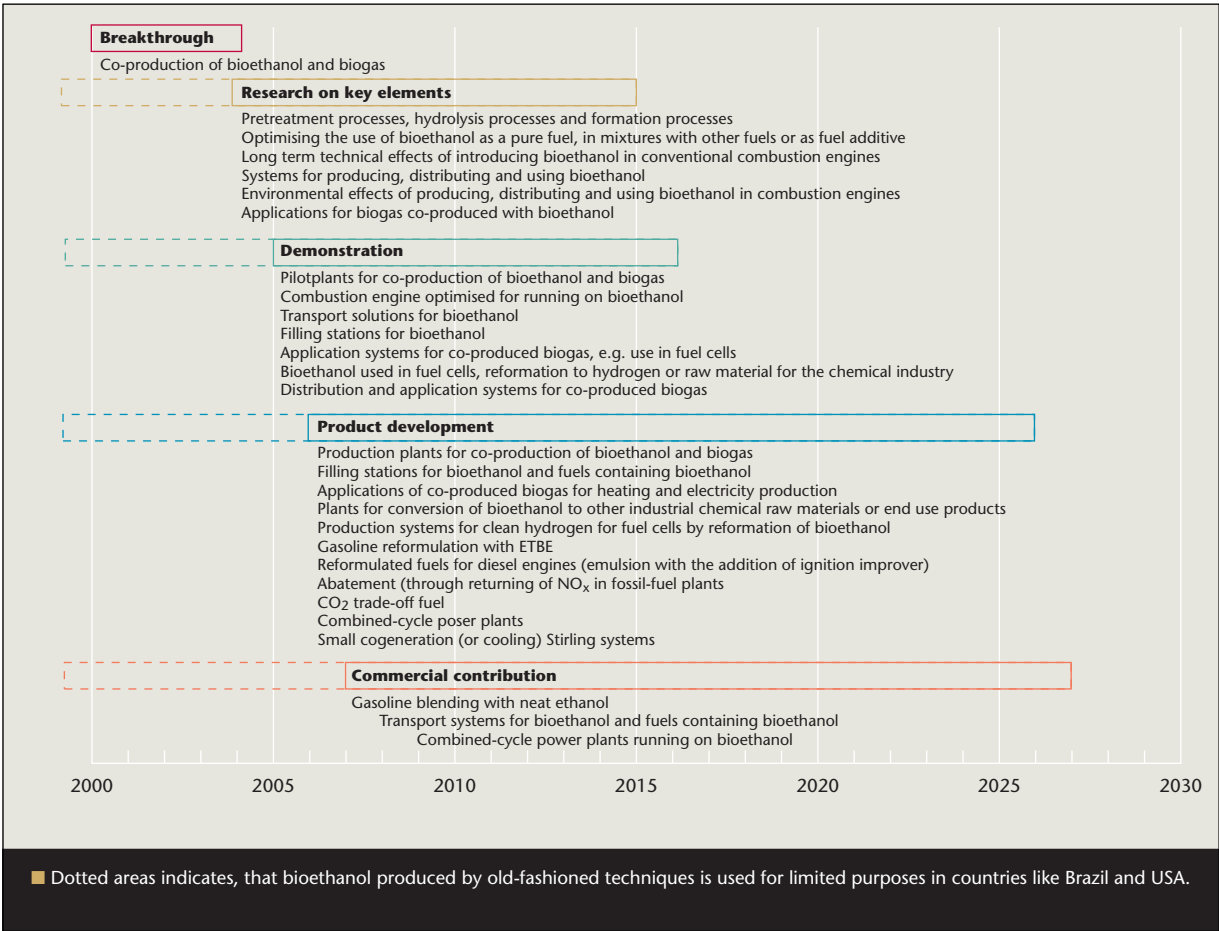
concerning sustainability of fuel and CO₂ reduction in the transport sector suggests that, in 2005, 2% of all gasoline and diesel is substituted by biofuels e.g. bioethanol, and in 2010, 5.75% will be substituted. MTBE can be replaced by ethanol. A total substituting of MTBE in USA and in Europe according to the suggestions of the directives creates a new ethanol market on respectively 53 and 12 billion litres of ethanol per year (Table 14). This need will be difficult to meet by the conventional ethanol production methods without increasing the prices on corn and wheat. Bioethanol based on fer-

mentation of biomass (in form of waste and energy crops) is a solution to this problem. However more research is still needed especially to reduce the cost or efficiency of commercial enzymes or, as another option, more efforts should be made to produce on-site enzymes as a part of the ethanol production. It has been shown that enzymes produced on the biomass to be used as raw material for ethanol fermentation are more efficient than commercial enzymes grown on artificial substrates (Thygesen et al 2003).

Table 14. Estimation of bioethanol production for transport and number of plants in 1005 and 2010 (numbers from IEA/DOE).

EU and USA bioethanol forecast	2005 EU/USA	2010 EU/USA
Gasoline consumption per year (bill. litres, IEA/DOE numbers)	145/545	142/619
Target case (2% in 2005 and 5,75% in 2010)		
Bioethanol required volume basis (bill. litres/year current trend)	4.3/16	12/53
Number of conventional ethanol plants required (at 250 bill. Litres/year using corn or wheat)	4/65	11/213
Percentage of required crops allocated for ethanol (wheat, corn, barley, sugar beets)	7/15	20/49

Figure 19. Bioethanol technologies and their time scale from breakthrough to commercial contribution.



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